UNIVERSITI PUTRA MALAYSIA

STRUCTURAL, THERMAL AND OPTICAL PROPERTIES OF ZINC BORO-ALUMINOSILICATE GLASSES FOR OPTICAL POWER AMPLIFICATION

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By

KAWA MUDHHER

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Chairman : Sharudin Omar Baki, PhD
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Recently, glasses doped with different rare earth (RE) ions are considered promising materials for lasers and optical amplifier applications. In order to investigate new candidate glasses for optical wave guide, structural, thermal, and optical properties of zinc boro-aluminosilicate glasses have been prepared in addition to different alkali (Li, Na, and K) and alkaline oxides (Mg, Ca, Sr, and Ba). Ten mol% of alkali and alkaline oxides were incorporated into Zinc boro-aluminosilicate glasses within high optical quality. Glasses were fabricated using melt-quenching method and prepared into two forms: well-polished solid state and powders. Samples were characterized using X-ray Diffraction (XRD), attenuated total reflectance-fourier transform infrared (ATR-FTIR) spectroscopy, Raman spectroscopy, thermo-gravimetric analysis (TGA), differential scanning calorimetry (DSC), and optical absorption spectroscopy. The presence of various functional groups such as triangular and tetrahedral-borate (BO_3 and BO_4) were confirmed by ATR-FTIR and Raman spectra. TGA analysis presented low weight loss for all synthesized glasses. From the DSC profiles the glass transition temperature (T_g), onset crystallization temperature (T_x), and crystallization temperature (T_c), were identified and different related thermal parameters were evaluated. From the optical absorption spectra, cut-off wavelength was calculated, showing a spectral shifting to longer wavelength with alkali (Li→Na→K), and alkaline (Mg→Ca→Sr→Ba) modifiers. Optical band gap energy was also investigated for allowed transitions in UV-Visible region using two methods: indirect and absorption spectrum fitting (ASF). Consequently, it was difficult to designate the best host among seven samples to dope with Rare Earth ions. Based on that, Er^{3+} was doped with the lowest cut-off wavelength glasses among alkali and alkaline, which are H1 and H4 with Li_2O and MgO, respectively. A total of 10 glasses were prepared using melt−quenching techniques with the compositions of $(40\text{-}x)B_2O_3 - 10SiO_2 - 10Al_2O_3 - 30ZnO - 10Li_2O - xEr_2O_3$ and $(40\text{-}x)B_2O_3 - 10SiO_2 - 10Al_2O_3 - 30ZnO$

– 10MgO − xEr_2O_3 (mol %) (x= 0.1, 0.25, 0.5, 1.0, and 2.0). Amorphous-like structure was observed for all the prepared glasses using XRD. In order to study the functional groups of the glass composition after the melt-quenching process, Raman spectroscopy was used. All samples were characterized using optical absorption for UV, visible and NIR region. Judd-Ofelt (JO) intensity parameters (Ω_λ, λ=2, 4 and 6) were calculated from the optical absorption spectra of two glasses, LiEr 2.0 and MgEr 2.0, which was doped with 2 mol % of Er^{3+}.

Furthermore, using Judd–Ofelt intensity parameters, the radiative A (s^{-1}), branching ratio (β), radiative decay lifetimes τ_{rad} (μs) of emissions from excited Er^{3+} ions in LiEr 2.0 and MgEr 2.0 to all lower levels were obtained in this work. In order to investigate these glasses for visible laser applications (green emission), quantum efficiency (η) of $^4I_{13/2}$ and $^4S_{3/2}$ levels of LiEr 2.0 and MgEr 2.0 were calculated, with and without $^4D_{7/2}$, using the radiative decay lifetimes $\tau_{rad.}$ (μs) and measured lifetimes $\tau_{exp.}$ (μs). Visible photoluminescence was measured under 377 nm excitation for both LiEr and MgEr glass series within the region of 390−580 nm. Decay lifetimes for emissions at 407 nm, 530 nm, and 554 nm were measured, showing single exponential behavior for all the LiEr and MgEr glass series. Lastly, following the photoluminescence and radiative decay lifetimes (τ_{rad}), full-width at half-maximum (FWHM), emission cross-section (σ_P^E) and bandwidth gain (FWHM × σ_P^E) parameters were calculated. Near-infrared photoluminescence under 980 nm excitation was measured for all the LiEr and MgEr glass series in the region of 1420−1620 nm. NIR emissions showed a broadband centered at ~ 1530 nm due to the transition of Er^{3+}: $^4I_{13/2} \rightarrow {}^4I_{15/2}$. Decay lifetimes for NIR emission at ~1530 nm were measured, presenting a single exponential nature for all the LiEr and MgEr glass series.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SIFAT-SIFAT STRUKTUR, TERMA DAN OPTIK KACA-KACA ZINK BORO-ALUMINOSILIKAT UNTUK KEGUNAAN PENGGANDA KUASA OPTIK

Oleh

KAWA MUDHHER

Januari 2018

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Terkini, kaca yang didopkan dengan pelbagai ion nadir bumi (RE) dicadangkan sebagai bahan yang berpotensi untuk kegunaan laser dan pengganda optik. Bagi tujuan penyelidikan terhadap pemilihan kaca-kaca terbaru untuk pemanduan gelombang optik, sifat-sifat struktur, terma, dan optik kaca-kaca zink boro-aluminosilikat dengan kepelbagaian alkali (Li, Na, K) dan oksida alkalin (Mg, Ca, Sr, dan Ba) telah dihasilkan. Sejumlah 10 % mol oksida-oksida alkali dan alkalin telah dimasukkan ke dalam kaca-kaca zink boro-aluminosilikat dengan dicirikan oleh kualiti optik yang tinggi. Kaca-kaca telah dihasilkan melalui kaedah leburan-lindap. Dua bentuk hasil kaca-kaca telah disediakan: bentuk pepejal yang digilap dan serbuk.

Sampel-sampel telah dicirikan menggunakan pembelauan sinar-X (XRD), spektroskopi jumlah pantulan dilemahkan Fourier inframerah (ATR-FTIR), spektroskopi Raman, analisis Thermo-gravimetrik (TGA), pengimbasan pembeza kalorimetri (DSC) dan spektroskopi penyerapan optik. Kehadiran pelbagai kumpulan-kumpulan fungsian seperti segi tiga dan tetrahedron-borat (BO_3 dan BO_4) telah disahkan oleh ATR-FTIR dan spektrum Raman. Analisis TGA mendapati kehilangan berat yang rendah bagi semua kaca-kaca yang telah dihasilkan; dapatan profail DSC telah mengenal pasti suhu peralihan kaca (T_g), permulaan suhu penghabluran (T_x) dan suhu penghabluran (T_c), di mana penilaian pelbagai parameter-parameter terma berkaitan telah dijalankan. Melalui spektra penyerapan optik, panjang gelombang pintasan telah ditentukan dan menunjukkan anjakan spektrum kepada panjang gelombang yang lebih besar untuk pengubahsuai alkali (Li→Na→K) dan alkalin (Mg→Ca→Sr→Ba). Jurang tenaga optik telah diselidiki untuk peralihan dibenarkan dalam julat UV-Nampak menggunakan dua kaedah; tidak-langsung dan pemadanan spektrum penyerapan (ASF). Hasil dapatan mendapati adalah sukar menentukan

sampel hos yang terbaik di antara tujuh sampel-sampel untuk didopkan dengan ion-ion nadir bumi. Atas asas di atas, Er^{3+} telah didopkan dengan kaca-kaca dengan pintasan panjang gelombang terendah, di kalangan alkali-alkalin H1 dan H4, masing-masing dengan LiO_2 dan MgO. Sejumlah 10 kaca-kaca telah disediakan melalui kaedah leburan-lindap dengan komposisi-komposisi (40-x) B_2O_3 - $10SiO_2$ - $10Al_2O_3$ - 30ZnO - $10Li_2O$ - xEr_2O_3 dan (40-x) B_2O_3 - $10SiO_2$ - $10Al_2O_3$ - 30ZnO - 10MgO - xEr_2O_3 (mol %) (x = 0.1, 0.25, 0.5, 1.0, dan 2.0). Struktur amorfus telah disahkan untuk kesemua kaca-kaca tersedia menggunakan XRD. Bagi mengkaji kumpulan fungsian komposisi-komposisi kaca-kaca setelah proses leburan-lindap, spektroskopi Raman telah digunakan. Kesemua sampel-sampel telah dicirikan melalui penyerapan optik untuk julat UV, nampak dan NIR. Parameter keamatan (Ω_λ, λ = 2, 4 dan 6) Judd-Ofelt (JO) telah ditentukan daripada spektra penyerapan optik untuk dua kaca, LiEr 2.0 dan MgEr 2.0 yang didopkan dengan 2 mol% Er^{3+}.

Didapati juga, melalui parameter-parameter keamatan JO, parameter-parameter kebarangkalian sinaran A (s^{-1}), nisbah cabangan (β), susutan hayat sinaran τ_{rad} (µs) daripada aras teruja ion Er^{3+} di dalam LiEr 2.0 dan MgEr 2.0 ke aras lebih rendah telah diperolehi di dalam kajian ini. Bagi menyelidiki kaca-kaca yang diperolehi untuk kegunaan laser nampak (pancaran hijau), kecekapan kuantum (η) aras-aras $^4I_{13/2}$ dan $^4S_{3/2}$ LiEr 2.0 dan MgEr 2.0 telah ditentukan untuk kewujudan dan tanpa kewujudan $^4D_{7/2}$, menggunakan susutan sinaran hayat $\tau_{rad.}$ (µs) dan ukuran hayat yang diukur, $\tau_{exp.}$ (µs). Fotoluminesen nampak telah diukur pada pengujaan 377 nm untuk kedua-dua siri kaca LiEr dan MgEr dalam julat 390-580 nm. Susut hayat untuk pancaran-pancaran pada 407 nm, 530 nm, dan 554 nm telah diukur dan kesemuanya menunjukkan sifat eksponen tunggal untuk kesemua siri kaca LiEr dan MgEr. Akhirnya, berdasarkan fotoluminesen dan susutan hayat sinaran (τ_{rad}), parameter-parameter lebar penuh pada separuh maksimum (FWHM), keratan-rentas pancaran (σ_P^E) dan gandaan lebar-jalur (FWHM × σ_P^E) telah ditentukan. Fotoluminescence inframerah-dekat (NIR) pada pengujaan 980 nm telah diukur untuk kesemua siri kaca LiEr dan MgEr di dalam julat 1420-1620 nm. Pancaran NIR menunjukkan jalur lebar berpusat pada ~ 1530 nm disebabkan oleh peralihan Er^{3+}: $^4I_{13/2} \rightarrow {}^4I_{15/2}$. Susut hayat untuk pancaran NIR pada ~ 1530 nm telah diukur dan menunjukkan sifat eksponen tunggal untuk kesemua siri kaca LiEr dan MgEr.

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I certify that a Thesis Examination Committee has met on 29 January 2018 to conduct the final examination of Kawa Mudhher on his thesis entitled "Structural, Thermal and Optical Properties of Zinc Boro-Aluminosilicate Glasses for Optical Power Amplification" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

RE	Rare Earth
XRD	X-ray Diffraction
ATR-FTIR	Attenuated Total Reflectance-Fourier Transform Infrared
TGA	Thermo-Gravimetric Analysis
DSC	Differential Scanning Calorimetry
T_g	Transition Temperature
T_x	Crystallization Temperature
T_m	Melting Temperature
VIS	Visible
UV	Ultra Violet
ASF	Absorption Spectrum Fitting
Er^{3+}	Erbium ions
NIR	Near Infrared
JO	Judd-Ofelt
Ω_λ	JO Intensity Parameters
A (S^{-1})	Radiative Probability
β	Branching Ratio
τ_{rad}	Radiative Decay Lifetimes
η	Quantum Efficiency
$\tau_{exp.}$	Measured Lifetimes
PL	Photo Luminescence
PLE	Photo Luminescence Excitation
FWHM	Full-Width at Half-Maximum

σ_P^E	Emission Cross-Section
RI	Refractive Indices
MW	Molecular Weight
$f_{exp.}$	Oscillator Strengths Measured
$f_{cal.}$	Oscillator Strengths Calculated
λ_P	Peak position
TTT	Time-Temperature-Transformation
ESA	Excited State Absorption
LD	Laser Diode
$\alpha(\lambda)$	Optical Absorption Coefficient
SSL	Sold-State Laser
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
CN	Co-ordination Number
RNM	Random Network Model
Ø	Bridging Oxygen
NBO	Non-Bridging Oxygen
TDA	Differential Thermal Analysis
Δ	Glass Stability Factor
H_R	Huruby's Parameter
n_D	Refractive Indices at wavelength of 589.3 nm
$\rho(v)$	Radiation Density
Γ	Orbital Angular Momentum

J	Total Angular Momentum
OD	Optical Density
ED	Electric Dipoles
MD	Magnetic Dipoles
$S_{meas.}$	Measured Line Strength
$S_{ed.}$	Electric Dipole Line Strength
$S_{calc.}$	Theoretical Electric Dipole Line Strength
W_{nr}	Nonradiative Rate
p	Phonon Energy
CR	Cross Relaxation
ΔE	Energy Gap
I_{em}	Light Intensity
ρ_L	Liquid Density
D.W.	Distilled Water
V_M	Molar Volume
OPD	Oxygen Packing Density
Rm	Molar Refractivity
M	Metallization Criterion
RL	Reflection Loss
αm	Molar Polarizability
$\wedge$	Glass Optical Basicity
γ	Basicity Moderating Parameter
Xi	Pauling Electronegativity

CHAPTER 1

INTRODUCTION

1.1 Optical glasses

Recently, optical glasses gained much attention for different technological and scientific applications. Optical glasses show higher stability when compared to polymers, wide range of temperature operations and better physical properties [1].

Optical glasses have found applications in radiation shielding, solid-state lasers, solar energy utilization and data transmission. Glasses became more interesting in data transmission compared to crystals due to the amorphous nature of the glass, which gives broadband of tens of nanometers, while crystals with long atomic range show sharp peaks resulting in only a few nanometers. Moreover, optical fiber waveguides crystals could produce light reflection, which affects data transmission [2−5].

Glasses show promising features for optical amplifiers in telecommunication, with an ability of transmitting gigabits of optical data. This made it to become the main network element as optical fiber waveguide or optical amplifiers and solid-state laser [5]. Apart from economic benefits, the increasing demand for new optical material systems leads to focus on developing compact, multifunctional features, which are capable of transmitting huge number of data information with higher speed, longer distances, and higher accuracies than traditional equipment [1].

Optical materials have played an important role in these advances and promised even greater impact in the future. In signal processing and transmission, the benefits of optical over electronic techniques have already changed modern lives in a major way by allowing access to the information super-highway. This advancement results from the development of novel optical materials that could not only handle larger signal bandwidth but also transmit a great number of communication channels over global distances. The linearity of the transmission media allows the superposition of optical signals without mixing, thus making a possibility of processing massive amounts of data simultaneously and in parallel. The materials that exhibit a strongly nonlinear response to optical radiation make possible the development of large optical memories, optical switches, and computational logic operations. Complex logic processes such as image analysis could be executed more quickly and accurately optically rather than electronically, using signal-processing operations such as amplification, wavelength-division multiplexing, and switching [1, 5].

Intense research efforts have been currently under way to integrate multiple optical technologies on-chip. One can easily envision a system in which optical signals are generated by micro-lasers modulated by light-signal modulators, transmitted and shaped by thin-film digital lenses, coupled into optical waveguide channels by nonlinear optical switches, analyzed by optical logic gates that work as part of complex neural network logic systems, and finally, stored as information in three-dimensional holographic data-storage media, all within the space of a computer chip.

1.2 Rare-Earth-doped glasses

Glasses are considered optical materials that could be used to manipulate the flow of light. These changes could be absorbing, reflecting, splitting or focusing the optical beam. In order to manipulate the injected light, the necessity of materials such as rare-earth-doped glasses has started to gain much attention, being implemented in variety of optical amplification applications. Once the light passes through the medium doped with rare-earth, it will excite these ions into another higher energy level [6].

Recently, the rapid growth of advanced optical communication networks became the hotspot for researchers to cover the increasing demand of information's technology. Optical signal transmission for telecommunications has been conducted at 1550 nm. Long communication distances require optical amplifiers, which in turn require finding and improving optical materials' extensibility in order to carry on the high-speed capacity, broadband wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) for optical amplifier usage where wide and flat gain spectrum became an important key in optical telecommunication [7, 8].

In order to study optical amplification at several desired optical frequencies, it is necessary to understand the population inversion mechanism of rare-earths. Generally, rare-earth ions can be classified into two groups. The first one is used as a main dopant such as; Nd^{3+} (900-950, 1030-1100 and 1320-1350) nm, Yb^{3+} (980-1100) nm, Er^{3+} (550, 1500-1600 and 2700) nm, Tm^{3+} (480, 800, 1450-1530 and 1700-2100) nm, Ho^{3+} (2100 and 2800-2900) nm, Pr^{3+} (490, 520, 600, 635 and 1300) nm and Ce^{3+} (280 and 330) nm. While the second group used as co-dopant which contains; Y^{3+}, Sm^{3+}, Eu^{3+}, Gd^{3+}, Tb^{3+}, Dy^{3+} and Lu^{3+} [3,6, 9−12].

Rare-earths (REs) Er^{3+} [13], Tm^{3+} [14], and Yb^{3+} [15] doped glasses such as tellurite [16], germanate [17], silicate [18], phosphate [19], and borate [20] have started to gain more attention for optical amplifier applications in the communication bands (O-, E-, S-, C-, L- and U) [21]. RE-doped fibers have a variety of applications such as optical amplifiers, lasers, optical switches, and nonlinear devices [6, 22,23]. Er^{3+} has interesting emission cross-sections, band width, and transition levels.

Generally, Er^{3+} shows three emissions in ultraviolet, visible and infrared regions, with transitions at ${}^4I_{11/2}\rightarrow{}^4I_{13/2}$ at 3000 nm, ${}^4I_{13/2}\rightarrow{}^4I_{15/2}$ nearly at 1500 nm, and ${}^4S_{3/2}\rightarrow{}^4I_{15/2}$ at 550 nm, respectively, and the first transition used for medical purposes, while the second transition is applicable for third telecommunication window, and the last transition employed in display applications with green emission [24]. In fact, the third window in optical communication is called zero loss window, due to its minimum loss.

The EDFA (erbium doped fiber amplifier) can cover 1500-1600 nm, which is an efficient repeater for long-distance communications. Generally, optical fiber amplifiers behave as a laser source, forming into cavities at various intervals in a continuous fiber by using photosensitive gratings. It is well known that exciting Er^{3+} energy levels between $^4I_{15/2}$ and $^4I_{11/2}$ with 980 nm wavelength can give emission at about 1550 nm due to the relaxation from $^4I_{13/2}$ to ground state $^4I_{15/2}$. This highlights the role of EDFA as the key for global communication with considerable cost [25].

1.3 Problem statement

Borosilicate glasses are considered low cost materials that are available commercially in large quantities by several vendors. Besides that, they can be easily produced in different compositions based on the application. Additionally, these glasses showed their ability for ion-exchange which made them suitable host for different optical applications. Moreover, borosilicate has refractive indices close to that of silica (n_D of Borosilicate = ~1.473 and n_D of silica = 1.458) which decrease the losses in connecting borosilicate and optical fiber-based silica, which is the base material used for optical fibers in existing telecommunication networks. Consequently, borosilicate glasses present an interesting platform for the development of integrated optical and microwave circuits [26].

Light dispersion in optical waveguide materials can occur due to the variation of the refractive indices with wavelength, which is a fundamental parameter in all optical materials including silica or borosilicate glasses. Silica glasses have been used for optical telecommunication network for three decades. The refractive indices is measured at specific wavelength lying within the transmission region, with sufficient accuracy. It is necessary to compare the measured refractive indices values with those calculated through empirical or mathematical expression to make it more accurate. Table 1.1 presents refractive indices values of different types of silica, borosilicate and tellurite glasses. It is clear that borosilicate has refractive indices matching silicates, making these glasses good candidates as hosts in optical applications.

Table 1.1 : Refractive indices of different glass compositions where fibers have been successfully produced

Glass composition (mol %)	Refractive indices
19.9 Na_2O – 9.1 CaO – 71 SiO_2	1.518 (n_D)
30 Na_2O – 10MgO – 60 SiO_2	1.5138 (n_D)
16 Na_2O – 6 Al_2O_3 – 89 SiO_2	1.499 (n_D)
16.9 Na_2O – 32 B_2O_3 – 50.6 SiO_2	1.525 (n_D)
44 Na_2O – 22.6 Al_2O_3 – 31 P_2O_3 – 2 PbO – 0.4 Er_2O_3	1.5037 (n_D)
5 Na_2O – 20 ZnO – 75 TeO_2	2.031 (633 nm)

(Source : Hewak. 1998)

The current EDFA is manufactured using silicate host glass that has phonon energy around 1200 cm^{-1} [25]. Recent researchers found that with host glass having higher phonon energy, more probability to bridge the energy difference in RE dopant such as the Er^{3+}:$^4I_{11/2}$→$^4I1_{3/2}$ could occur [27]. Moreover, the intensity at 1.5 µm region of Er^{3+}-doped glasses were found to be quenched whenever the concentration of Er^{3+} crosses 1.0 mol% [28]. Additionally, the available EDFA based silicate glasses show about 40 nm bandwidth, which is considered as one of the limitations of the EDFA.

In fact, current available lasers are restricted to be used for display purposes due to the high power of amplifying, which can be hazardous on eye or skin [28]. Erbium doped glasses emitting in the visible region with wavelength range of 510-570 nm, which can be a safe source for green laser emission since it has limited power [30].

In the present thesis, prepared glasses covered the 3rd window (low loss) of optical telecommunication using Er^{3+} ions containing boro-silicate glasses with different modifier oxides such as (Al, Zn and alkali-alkaline). It is well known that borate glass possesses phonon energy around 1400 cm^{-1} which can enhance the non-radiative energy transfer processes through energy diffusion, leading to a reduction in the quantum efficiency which limits the emission intensity, while additional glass former with lower phonon energy can reduce the non-radiative transition probability substantially [8].

1.4 Objectives

In this thesis, visible and NIR optical band of Er^{3+} doped zinc boro-aluminosilicate glasses have been investigated systematically with additional alkali/alkaline modifiers in order to explore new lasers and EDFA candidate. The main objectives of this thesis can be concluded as follows:

(i). In order to investigate a new suitable candidate as host glass to be doped with Er^{3+}, structural, thermal and optical features of zinc boro-aluminosilicate glasses have been studied systematically with different alkali and alkaline modifiers.
(ii). Visible laser emissions of Er^{3+} doped zinc boro-aluminosilicate and (Li_2O/MgO) modifiers have been investigated with different concentrations of Er^{3+}.
(iii). NIR emissions for the fabricated glasses have been studied furthermore to find the modifier, which offer highest emission to be obtained as 1.5 µm broadband optical amplifier.

1.5 Thesis outlines

In this section, the six chapters of the present thesis are outlined as follows:

Chapter 1 presents the overview of optical materials based on oxide glasses and their features in different applications. Additionally, RE-doped optical glasses were reviewed based on the features of Er^{3+} in broadband optical amplifiers. Moreover, the problem statement and the main objectives of this thesis are also mentioned.

Chapter 2 reviews fundamental information about glass forming. Glass formers which play an important role for optical materials (e.g., glasses), reviewed in this chapter, are borate, silicate and boro-silicate glasses. In this part, the reason for choosing boro-silicate as a glass former in order to achieve the research objectives is explained. The role of Er^{3+} is discussed in detail.

Chapter 3 presents the RE phenomena and some of its fundamental characteristics, which are very important resources in this study especially for the role of Er ions in the boro-silicate glass host. In the beginning, the basic RE spectroscopic theory is presented, which accounts for the observed intensity absorption spectra of the rare-earth ions in solids. This is followed by the theory of Judd-Ofelt where the related absorption intensity parameters Ω_t (t = 2, 4, 6) are obtained through a comprehensive numerical calculation procedure. Moreover, energy transfer and ions interaction is explained for Er^{3+} doped host glasses.

Chapter 4 highlights the glass sample preparation and method of characterizations. The detailed steps of important preparation procedure are described here. Starting with glass sample calculations, followed by batching procedure, and glass fabrication are clearly explained systematically. The particulars of the material characterizations for structural, thermal and optical analysis including the instrumentation are also specified.

Chapter 5, investigates the effect of alkali-alkaline on broadband amplification, being divided into two sections. Firstly, section 5.1 presents the structural, thermal and optical properties of zinc boro-aluminosilicate glass introduced with additional 10 mol% of alkali-alkaline, as a result, it shows that all those glasses have similar structural and thermal properties. Later, the purpose of choosing Li_2O and MgO among alkali-alkaline, is mentioned respectively. Finally, section 5.2 presents Er^{3+} doped zinc boro-aluminosilicate with additional 10 mol% of Li_2O/MgO. In this section, Visible and NIR emission with related Decay lifetimes is presented. The result identified Li_2O as the highest emission compared to MgO in both visible and NIR regions.

Chapter 6 concludes the findings of the thesis. The results of all systematic objectives are presented in order to obtain a suitable host glass for optical amplifier so it can be employed for green emission and the 3rd window of optical communication.

REFERENCES

[1] J. H. Simmons and K. S. Potter, *Optical Materials*. 2000.

[2] K. Kirdsiri, J. Kaewkhao, N. Chanthima, and P. Limsuwan, "Comparative study of silicate glasses containing Bi_2O_3, PbO and BaO: Radiation shielding and optical properties," *Ann. Nucl. Energy*, vol. 38, no. 6, pp. 1438–1441, 2011.

[3] W. F. Krupke, "Ytterbium solid-state lasers - the first decade," *IEEE J. Sel. Top. Quantum Elect.,* vol. 6, no. 6, pp. 1287-1296, 2000.

[4] Z. He, C. Zhong, S. Su, M. Xu, H. Wu, Y. Cao, A. K. K. A. Kyaw, D. D. H. Wang, V. Gupta, J. Zhang, S. Chand, G. C. Bazan, and A. J. Heeger, "Enhanced power-conversion efficiency in polymer solar cells using an inverted device structure," *Nat. Photonics*, vol. 25, no. 17, pp. 593–597, 2013.

[5] P. F. Wysocki, J. B. Judkins, R. P. Espindola, M. Andrejco, and A. M. Vengsarkar, "Broad-band erbium-doped fiber amplifier flattened beyond 40 nm using long-period grating filter," *IEEE Photonics Technol. Lett.*, vol. 9, no. 10, pp. 1343–1345, 1997.

[6] G. Lakshminarayana, K. M. Kaky, S. O. Baki, S. Ye, A. Lira, I. V. Kityk, and M. A. Mahdi, "Concentration dependent structural, thermal, and optical features of Pr^{3+}-doped multicomponent tellurite glasses," J. Alloys Compd., vol. 686, pp. 769–784, 2016.

[7] S. Tanabe, "Rare-earth-doped glasses for fiber amplifiers in broadband telecommunication," *Comptes Rendus Chim.*, vol. 5, no. 12, pp. 815–824, 2002.

[8] Q. Chen, M. Ferraris, D. Milanese, Y. Menke, E. Monchiero, and G. Perrone, "Novel Er-doped PbO and B_2O_3 based glasses: Investigation of quantum efficiency and non-radiative transition probability for 1.5 μm broadband emission fluorescence," *J. Non. Cryst. Solids*, vol. 324, no. 1–2, pp. 12–20, 2003.

[9] D. S. Da Silva, T. A. A. De Assumpção, L. R. P. Kassab, and C. B. De Araújo, "Frequency upconversion in Nd^{3+} doped PbO-GeO_2 glasses containing silver nanoparticles," *J. Alloys Compd.*, vol. 586, no. SUPPL. 1, pp. 2012–2015, 2014.

[10] V. A. G. Rivera, M. El-Amraoui, Y. Ledemi, Y. Messaddeq, and E. Marega, "Expanding broadband emission in the near-IR via energy transfer between Er^{3+}-Tm^{3+} co-doped tellurite-glasses," *J. Lumin.*, vol. 145, pp. 787–792, 2014.

[11] J. Yan, C. Lin, and S. Yang, "Luminescence Properties of Tm^{3+} and Eu^{3+} Co-doped $LaPO_4$ Phosphor for White-Light Emission," *Next-Generation Electronics (ISNE), International Symposium on IEEE*, pp. 5-7, 2014.

[12] T. Li, C. F. Guo, Y. M. Yang, L. Li, and N. Zhang, "Efficient green up-conversion emission in Yb^{3+}/Ho^{3+} co-doped $CaIn_2O_4$," *Acta Mater.*, vol. 61, no. 19, pp. 7481-7487, 2013.

[13] W. J. Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500-nm," *IEEE J. Light. Technol.*, vol. 9, no. 2, pp. 234-250, 1991.

[14] M. Naftaly, S. Shen, and a Jha, "Tm^{3+}-Doped Tellurite Glass for a Broadband Amplifier at 1.47 nm.," *Appl. Opt.*, vol. 39, no. 27, pp. 4979-4984, 2000.

[15] R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," *IEEE J. Quantum Electron.*, vol. 33, no. 7, pp. 1049–1056, 1997.

[16] K. Maheshvaran, S. Arunkumar, V. Sudarsan, V. Natarajan, and K. Marimuthu, "Structural and luminescence studies on Er^{3+}/Yb^{3+} co-doped boro-tellurite glasses," *J. Alloys Compd.*, vol. 561, pp. 142–150, 2013.

[17] T. Wei, F. Chen, Y. Tian, and S. Xu, "1.53 μm emission properties in Er^{3+} doped Y_2O_3 and Nb_2O_5 modified germanate glasses for an optical amplifier," *J. Lumin.*, vol. 154, pp. 41-45, 2014.

[18] Y. Fujimoto and M. Nakatsuka, "Optical amplification in bismuth-doped silica glass," *Appl. Phys. Lett.*, vol. 82, no. 19, pp. 3325-3326, 2003.

[19] S. Jiang, T. Luo, B. C. Hwang, F. Smekatala, K. Seneschal, J. Lucas, and N. Peyghambarian, "Er^{3+}-doped phosphate glasses for fiber amplifiers with high gain per unit length," *J. Non. Cryst. Solids*, vol. 263, pp. 364-368, 2000.

[20] W. A. Pisarski, J. Pisarska, R. Lisiecki, Ł. Grobelny, G. Dominiak-Dzik, and W. Ryba-Romanowski, "Erbium-doped oxide and oxyhalide lead borate glasses for near-infrared broadband optical amplifiers," *Chem. Phys. Lett.*, vol. 472, no. 4-6, pp. 217-219, 2009.

[21] B. Chen, L. Shen, H. Lin, E. Yue, and B. Pun, "Signal amplification in rare-earth doped heavy metal germanium tellurite glass fiber," *J. Opt. Soc. Am. B*, vol. 28, no. 10, pp. 2320-2327, 2011.

[22] C. R. Giles and E. Desurvire, "Modeling Erbium-Doped Fiber Amplifiers SP ," vol. 9, no. 2, 1991.

[23] G. Lakshminarayana, K. M. Kaky, J. Jedryka, A. M. El-Naggar, A. A. Albassam, G. Myronchuk, and M. A. Mahdi, "Laser induced elastooptics in novel Bi_2O_3 and Pr_2O_3 doped tellurite rich glasses," *Mater. Lett.*, vol. 183, pp. 322-324, 2016.

[24] Y. C. Yan, a. J. Faber, H. de Waal, P. G. Kik, and a. Polman, "Erbium-doped phosphate glass waveguide on silicon with 4.1 dB/cm gain at 1.535 μm," *Appl. Phys. Lett.*, vol. 71, no. 20, pp. 2922-2924, 1997.

[25] L. J. Q. Maia, J. C. V Santos, J. F. Carvalho, R. R. Gonçalves, A. C. Hernandes, and S. J. L. Ribeiro, "NIR luminescence from erbium doped (100-x)SiO_2:xZnO powders obtained by soft chemical synthesis," *J. Lumin.*, vol. 170, pp. 663-670, 2016.

[26] I. C. S. Carvalho, M. Fokine, C. M. B. Cordeiro, H. Carvalho, and R. Kashyap, "Borosilicate glass for photonics applications," *Opt. Mater. (Amst).*, vol. 30, no. 12, pp. 1816–1821, 2008.

[27] F. Yang, B. Huang, L. Wu, Y. Zhou, F. Chen, G. Yang, and J. Li, "Enhanced 1.53 μm radiative transition in Er^{3+}/Ce^{3+} co-doped tellurite glass modified by B_2O_3 oxide," *Opt. Mater. (Amst).*, vol. 47, pp. 149-156, 2015.

[28] S. N. Rasool, B. C. Jamalaiah, K. Suresh, L. R. Moorthy, and C. K. Jayasankar, "Spectroscopic properties of Er^{3+}-doped phosphate based glasses for broadband 1.54 μm emission," *J. Mol. Struct.*, vol. 1130, pp. 837-843, 2016.

[29] S. Alkharashi, Y. Alzahrani, E. B. Abboud, and S. R. Nowilaty, "Full-Thickness Macular Hole Secondary to High-Power Handheld Blue Laser: Natural History and Management Outcomes," 2015.

[30] K. Gürel, V. J. Wittwer, M. Hoffmann, C. J. Saraceno, S. Hakobyan, B. Resan, A. Rohrbacher, K. Weingarten, S. Schilt, and T. Südmeyer, "Green-diode-pumped femtosecond Ti : Sapphire laser with up to 450 mW average power," vol. 23, no. 23, pp. 30043–30048, 2015.

[31] Shelby, "Introduction to Glass Science and Technology," *Royal Society of Chemistry*, vol. 208, 2005.

[32] Pilkington Handbook, "Glass Handbook," NSG Gr., no. 2014, pp. 1–126, 2014.

[33] H. Yinnon and D. R. Uhlmann, "Applications of thermoanalytical techniques to the study of crystallization kinetics in glass-forming liquids, part I: Theory," *J. Non. Cryst. Solids*, vol. 54, no. 3, pp. 253–275, 1983.

[34] R.D.Shannon and C.T.Prewitt, "Effective ionic radii in oxides and fluorides," *Acta Cryst*, vol. 5, no. 25, pp. 925-946, 1969.

[35] W. H. Zachariasen, "The atomic arrangement in glass." *J. American Che. Soci.*, vol. 54, no. 10, pp. 3841-3851, 1932.

[36] D. R. Uhlmann, "Polymer glasses and oxide glasses," *J. Non. Cryst. Solids*, vol. 42, no. 1–3, pp. 119–142, 1980.

[37] J. E. Stanworth, "On the structure of glass." *J. Soc. Glass Technol*. no. 32, pp. 154-172, 1948.

[38] G. de Leede and H. de Waal, "Evaluation of glass formation criteria," J. Non. Cryst. Solids, vol. 104, no. 1, pp. 45–51, 1988.

[39] I. K. H. Sun, & M. L. Huggins, "Energy additivity in oxygen-containing crystals and glasses," *J. Phys. Chem.*, vol. 2, no. 51, pp. 438-443, 1947.

[40] AK. Varshneya, "Fundamentals of Inorganic Glasses," Gulf *Professional Publishing*, 1994.

[41] A. G. Smekal, "On the structure of glass," J. Soc. Glass Tech., no. 35, pp. 392-395, 1951.

[42] H. Rawson, "Inorganic glass-forming systems" *London: Academic press*, vol. 317, 1967.

[43] R. Busch, "The thermophysical properties of bulk metallic glass-forming liquids," *Jom*, vol. 52, no. 7, pp. 39-42, 2000.

[44] G. Lakshminarayana, S. Buddhudu, "Spectral analysis of Eu^{3+} and Tb^{3+}:B_2O_3–ZnO–PbO glasses," *Mat. Chem. Phy.*, no. 102, pp. 181-186, 2007.

[45] I. Pal, A. Agarwal, S. Sanghi, and M.P. Aggarwal, "Spectroscopic and radiative properties of Nd^{3+} ions doped zinc bismuth borate glasses,". *Indian Journal of Pure and Applied Physics*, vol. 1, no. 51, pp.18-25, 2013.

[46] J. Zmojda, M. Kochanowicz, P. Miluski, D. Dorosz, P. Jelen, and M. Sitarz, "Analysis of thermal and structural properties of germanate glasses co-doped with Yb^{3+}/Tb^{3+} ions," *Spectro. Acta Part A: Mole. Biom. Spect.*, no. 131, pp.702-707, 2014.

[47] M. Abdel-Baki, and F. El-Diasty, "Oxyfluoroborate host glass for upconversion application: phonon energy calculation," *Optical Review*, vol. 2, no. 23, pp.284-289, 2016.

[48] L.F. Shen, B.J. Chen, H. Lin, and E.Y.B. Pun, "Praseodymium ion doped phosphate glasses for integrated broadband ion-exchanged waveguide amplifier," *J. Alloys Comp.*, no. 622, pp.1093-1097, 2015.

[49] T. Vassilev, I. Penkov, C. Tzvetkova, and R. Pascova, "Glass transition temperatures and structures of multicomponent borate glasses: Influence of modifier cation field strengths," *J. Non. Cryst. Solids*, vol. 438, pp. 1-6, 2016.

[50] Y. Li, A. Matinmanesh, D. J. Curran, E. H. Schemitsch, P. Zalzal, M. Papini, A. W. Wren, and M. R. Towler, "Characterization and fracture property of different strontium-containing borate-based glass coatings for Ti6Al4V substrates," *J. Non. Cryst. Solids*, vol. 458, pp. 69-75, 2017.

[51] L. D. Pye, V. D. Fréchette, & N. J. Kreidl, "Borate glasses: structure, properties, applications" *Springer Science & Business Media*, vol. 12, 2012.

[52] R. E. Youngman, J. Kieffer, J. D. Bass, and L. Duffrène, "Extended structural integrity in network glasses and liquids," *J. Non. Cryst. Solids*, vol. 222, pp. 190-198, 1997.

[53] P. P. Pawar, S. R. Munishwar, and R. S. Gedam, "Intense white light luminescent Dy^{3+} doped lithium borate glasses for W-LED: A correlation between physical, thermal, structural and optical properties," *Solid State Sci.*, vol. 64, pp. 41-50, 2016.

[54] D. Hewak, "Properties, Processing and Application of Glass and Rare Earth Glasses for Optical Fibers," *INSPEC*, 1998.

[55] I. Fanderlik, "Silica glass and its application," vol. V, no. 11, 1991.

[56] J.-L. Auguste, G. Humbert, S. Leparmentier, M. Kudinova, P.-O. Martin, G. Delaizir, K. Schuster, and D. Litzkendorf, "Modified Powder-in-Tube Technique Based on the Consolidation Processing of Powder Materials for Fabricating Specialty Optical Fibers," *Materials (Basel).*, vol. 7, no. 8, pp. 6045–6063, 2014

[57] R. Brückner, "Properties and structure of vitreous silica. I," J. *Non. Cryst. Solids*, vol. 5, no. 2, pp. 123–175, 1970.

[58] L. G. Van Uitert, D. A. Pinnow, J. C. Williams, T. C. Rich, R. E. Jaeger, & W. H. Grodkiewicz, "Borosilicate glasses for fiber optical waveguides," Mate. Res. Bull., vol. 4, no. 8, pp. 469-476, 1973.

[59] K. Aiso, Y. Tashiro, T. Suzuki, and T. Yagi, "Development of Er / Yb Co-doped Fiber for High-Power Optical Amplifiers," *Furukawa Electr. Rev.*, vol. 20, pp. 41–45, 2001.

[60] P. C. Becker, N. A. Olsson, and J. R. Simpson, *Erbium doped fiber Amplifiers* . 2003.

[61] E. Snoeks, P. G. Kik, and A. Polman, "Concentration quenching in erbium implanted alkali silicate glasses," *Opt. Mater. (Amst)*., vol. 5, no. 3, pp. 159–167, 1996.

[62] S. Sudo, "Optical fiber amplifiers: materials, devices, and applications," *Artech house*, 1997.

[63] G. H. Dieke, "Spectra and energy levels of rare earth ions in crystals," *Eds. Henry Milton Crosswhite, and Hannah Crosswhite, New York: Interscience Publishers*, vol. 5, 1968.

[64] H. A. Kramers, "Paramagnetic rotation of the plane of polarisation in uniaxial crystals of the rare earths," *Proc. Koninkl. Akad. Wet. Amsterdam*, no. 32, pp. 1176-1189, 1929.

[65] B. R. Judd, "Optical absorption intensities of rare-earth ions," *Phys. Rev.*, vol. 127, no. 3, pp. 750–761, 1962.

[66] G. S. Ofelt, "Intensities of crystal spectra of rare-earth ions," *J. Chem. Phys.*, vol. 37, no. 1962, pp. 511–520, 1962.

[67] D. K. Sardar, J. B. Gruber, B. Zandi, J. A. Hutchinson, and C. Ward Trussell, "Judd-Ofelt analysis of the Er^{3+}(4f11) absorption intensities in phosphate glass: Er^{3+}, Yb^{3+}," *J. Appl. Phys.*, vol. 93, no. 4, pp. 2041–2046, 2003.

[68] W. T. Carnall, P. R. Fields, and B. G. Wybourne, "Spectral Intensities of the Trivalent Lanthanides and Actinides in Solution. I. Pr^{3+}, Nd^{3+}, Er^{3+}, Tm^{3+}, and Yb^{3+}," *J. Chem. Phys.*, vol. 42, no. 11, pp. 3797–3806, 1965.

[69] M. J. Weber, "Probabilities for radiative and nonradiative decay of Er^{3+} in LaF_3," *Phys. Rev.*, vol. 157, no. 2, pp. 262–272, 1967.

[70] B. M. Walsh, N. P. Barnes, D. J. Reichle, and S. Jiang, "Optical properties of Tm^{3+} ions in alkali germanate glass," *J. Non. Cryst. Solids*, vol. 352, no. 50–51, pp. 5344–5352, 2006.

[71] L. A. Riseberg, and M. J. Weber, "Relaxation phenomena in rare earth luminescence," *Progress in Optics*, no. 31, pp. 89, 1993.

[72] G. Blasse, and B. C. Grabmaier. Luminescent materials. *Springer Science & Business Media*, 2012.

[73] C. B. Layne, W. H. Lowdermilk, and M. J. Weber, "Multiphonon relaxation of rare-earth ions in oxide glasses," *Phys. Rev. B*, vol. 16, no. 1, pp. 10–20, 1977.

[74] W. J. Miniscalco, "Optical and Electronic Properties of Rare Earth Ions in Glasses," *Taylor & Francis*, 2001.

[75] G. Lakshminarayana, J. Qiu, M. G. Brik, G. A. Kumar, and I. V Kityk, "Spectral analysis of Er^{3+} -, Er^{3+} /Yb^{3+} - and Er^{3+} / Tm^{3+} / Yb^{3+} -doped TeO_2-ZnO-WO_3-TiO_2-Na_2O glasses," *J. Phys. Condens. Matter*, vol. 20, no. 37, p. 375101, 2008.

[76] B. Bhatia, S. L. Meena, V. Parihar, and M. Poonia, "Optical Basicity and Polarizability of Nd^{3+} -Doped Bismuth Borate Glasses," *New J. Glas. Ceram.*, vol. 5, no. July, pp. 44–52, 2015.

[77] N. Santha, S. Shamsudeen, N. T. Karunakaran, and J. Isuhak Naseemabeevi, "Spectroscopic, Dielectric and Optical Properties of 60ZnO-30B_2O_3-10SiO_2

Glass-Al_2O_3 Composites," *Int. J. Appl. Ceram. Technol.*, vol. 8, no. 5, pp. 1042–1049, 2011.

[78] I. Pal, A. Agarwal, S. Sanghi, and M. P. Aggarwal, "Spectroscopic and radiative properties of Nd^{3+} ions doped zinc bismuth borate glasses," *Ind. J. Pure Appl. Physi.*, vol. 51, pp. 18–25, 2013.

[79] S. S. Zulkefly, H. M. Kamari, M. N. A. Abdul Azis, and W. M. D. Wan Yusoff, "Influence of Erbium Doping on Dielectric Properties of Zinc Borotellurite Glass System," *Mater. Sci. Forum*, vol. 846, pp. 161–171, 2016.

[80] E. A. Kim, H. W. Choi, and Y. S. Yang, "Effects of Al_2O_3 on (1–x)[SrO – SiO_2 – B_2O_3] – xAl_2O_3 glass sealant for intermediate temperature solid oxide fuel cell," *Ceram. Int.*, vol. 41, no. 10, pp. 14621–14626, 2015.

[81] K. Swapna, S. Mahamuda, M. Venkateswarlu, A. Srinivasa Rao, M. Jayasimhadri, S. Shakya, and G. V. Prakash, "Visible, Up-conversion and NIR (~1.5 µm) luminescence studies of Er^{3+} doped Zinc Alumino Bismuth Borate glasses," *J. Lumin.*, vol. 163, pp. 55–63, 2015.

[82] A. I. Borhan, M. Gromada, G. G. Nedelcu, and L. Leontie, "Influence of additives (CoO , CaO , B_2O_3) on thermal and dielectric properties of BaO-Al_2O_3 -SiO_2 glass-ceramic sealant for OTM applications," pp. 36–40. *arXiv preprint arXiv:1507.03390* (2015).

[83] L. Balachander, G. Ramadevudu, M. Shareefuddin, R. Sayanna, and Y. C. Venudharc, "IR analysis of borate glasses containing three alkali oxides," *ScienceAsia*, vol. 39, no. 3, pp. 278–283, 2013.

[84] Y. A. Tanko, M. R. Sahar, and S. K. Ghoshal, "Results in Physics Prominent spectral features of Sm 3 + ion in disordered zinc tellurite glass," vol. 6, pp. 7–11, 2016.

[85] P. P. Pawar, S. R. Munishwar, and R. S. Gedam, "Physical and optical properties of Dy^{3+}/Pr^{3+} Co-doped lithium borate glasses for W-LED," *J. Alloys Compd.*, vol. 660, pp. 347–355, 2016.

[86] A. Wagh, Y. Raviprakash, V. Upadhyaya, and S. D. Kamath, "Composition dependent structural and optical properties of PbF_2–TeO_2–B_2O_3–Eu_2O_3 glasses," *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.*, vol. 151, pp. 696–706, 2015.

[87] E. R. Shaaban, M. Shapaan, and Y. B. Saddeek, "Structural and thermal stability criteria of Bi_2O_3–B_2O_3 glasses," *J. Phys. Condens. Matter*, vol. 20, no. 15, p. 155108, 2008.

[88] S. Kareem, M. A. Samee, S. M. Taqiullah, and S. Rahman, "FT-IR and Raman spectroscopic studies of ZnF_2 – ZnO – As_2O_3 – TeO_2 glasses," vol. 10, no. 3, pp. 329–339, 2016.

[89] N. S. Saetova, A. A. Raskovalov, B. D. Antonov, T. V. Yaroslavtseva, O. G. Reznitskikh, and N. I. Kadyrova, “The influence of lithium oxide concentration on the transport properties of glasses in the Li_2O-B_2O_3-SiO_2 system,” *J. Non. Cryst. Solids*, vol. 443, pp. 75–81, 2016.

[90] Y. B. Saddeek, A. M. Abousehly, and S. I. Hussien, “Synthesis and several features of the Na_2O-B_2O_3 -Bi_2O_3 -MoO_3 glasses,” *J. Phys. D. Appl. Phys.*, vol. 40, no. 15, pp. 4674–4681, 2007.

[91] W. A. Pisarski, T. Goryczka, J. Pisarska, and W. Ryba-Romanowski, “Er-doped lead borate glasses and transparent glass ceramics for near-infrared luminescence and up-conversion applications,” *J. Phys. Chem. B*, vol. 111, no. 10, pp. 2427–2430, 2007.

[92] L. Balachander, G. Ramadevudu, M. Shareefuddin, R. Sayanna, and Y. C. Venudharc, “IR analysis of borate glasses containing three alkali oxides,” *ScienceAsia*, vol. 39, no. 3, pp. 278–283, 2013.

[93] I. Ardelean, “FTIR structural investigation of $3B_2O_3 \cdot BaO$ glass matrix containing manganese ions,” *J. Optoele. Adv. Mate., vol.* 8, no. 3, pp. 1118–1120, 2006.

[94] D. Singh, K. Singh, G. Singh, Manupriya, S. Mohan, M. Arora, and G. Sharma, “Glasses,” *J. Phys. Condens. Matter*, vol. 20, no. 7, p. 75228, 2008.

[95] B. P. Dwivedi, M. H. Rahman, Y. Kumar, and B. N. Khanna, “Raman scattering study of lithium borate glasses,” *J. Phys. Chem. Solids*, vol. 54, no. 5, pp. 621–628, 1993.

[96] A. K. Yadav and P. Singh, “A Review on Structure of Glasses by Raman Spectroscopy,” *RSC Adv.*, vol. 5, pp. 67583–67609, 2015.

[97] L. Koudelka, P. Kalenda, P. MoŠner, Z. Černošek, L. Montagne, and B. Revel, “Structural investigation of BaO-B_2O_3-P_2O_5 glasses by NMR and Raman spectroscopy,” *J. Mol. Struct.*, vol. 1119, pp. 212–219, 2016.

[98] A. A. Osipov and L. M. Osipova, “Raman scattering study of barium borate glasses and melts,” *J. Phys. Chem. Solids*, vol. 74, no. 7, pp. 971–978, 2013.

[99] M. Subhadra and P. Kistaiah, “Infrared and Raman spectroscopic studies of alkali bismuth borate glasses: Evidence of mixed alkali effect,” *Vib. Spectrosc.*, vol. 62, pp. 23–27, 2012.

[100] A. Winterstein-Beckmann, D. Möncke, D. Palles, E. I. Kamitsos, and L. Wondraczek, “Raman spectroscopic study of structural changes induced by micro-indentation in low alkali borosilicate glasses,” *J. Non. Cryst. Solids*, vol. 401, pp. 110–114, 2014.

[101] M. C. Tobin, T. Bååk, “Raman Spectra of Vitreous B_2O_3 and of Some B_2O_3-Bi_2O_3-Al_2O_3 Glasses,” *JOSA*, vol. 60, no. 3, pp. 368-370, 1970.

[102] E. I. Kamitsos and G. D. Chryssikos, “Borate glass structure by Raman and infrare spectroscopies,” *J. Mol. Str.*, vol. 247, pp. 1–16, 1991.

[103] C. Scholten,P, “The structure of borosilicate glasses studied by Raman scattering,” *J. Non-Cryst. Solids*, vol. 2, no. 20, pp. 193–224, 1976.

[104] K. Fukumi, K. Ogawa, and J. Hayakawa, “Intensities of Raman bands in borate glasses,” *J. Non. Cryst. Solids*, vol. 151, no. 3, pp. 217–221, 1992.

[105] B. N. Meera, a. K. Sood, N. Chandrabhas, and J. Ramakrishna, “Raman study of lead borate glasses,” *J. Non. Cryst. Solids*, vol. 126, pp. 224–230, 1990.

[106] B. N. Meera and J. Ramakrishna, “‘Raman spectral studies of borate glasses,’ *J. Non-Cryst. Solids*, vol. 159, p. 1, 1993.

[107] M. Loubser, C. Strydom, and H. Potgieter, “A thermogravimetric analysis study of volatilization of flux mixtures used in XRF sample preparation,” *X-Ray Spectrom.*, vol. 33, no. 3, pp. 212–215, 2004.

[108] S. Feih, E. Boiocchi, G. Mathys, Z. Mathys, A. G. Gibson, and A. P. Mouritz, “Mechanical properties of thermally-treated and recycled glass fibres,” *Compos. Part B Eng.*, vol. 42, no. 3, pp. 350–358, 2011.

[109] R. Rajeswari, S. S. Babu, and C. K. Jayasankar, “Spectroscopic characterization of alkali modified zinc-tellurite glasses doped with neodymium,” *Spectrochim. Acta - Part A Mol. Biomol. Spectrosc.*, vol. 77, no. 1, pp. 135–140, 2010.

[110] D. R.Uhlmann, “Glass formation,” *J. Non-Cryst. Solids*, vol. 25 no. 3, pp.42-85. 1977.

[111] J. N. Ayuni, M. K. Halimah, Z. A. Talib, H. A. A. Sidek, W. M. Daud, A. W. Zaidan, and A. M. Khamirul, “Optical properties of ternary TeO2-B2O3-ZnO glass system,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 17, no. 1, 2011.

[112] B. Shan and Z. Chang, “Dramatic extension of the high-order harmonic cutoff by using a long-wavelength driving field,” *Phys. Rev. A - At. Mol. Opt. Phys.*, vol. 65, no. 1, p. 4, 2002.

[113] F. El-Diasty, F. A. Abdel Wahab, and M. Abdel-Baki, “Optical band gap studies on lithium aluminum silicate glasses doped with Cr3+ ions,” *J. Appl. Phys.*, vol. 100, no. 9, pp. 1–6, 2006.

[114] Iskandar, S.M., Halimah, M.K., Daud, W.M., Sidek, H.A.A. and Zaman, M.K., *Solid State Scie. Tech.*, vol. 18, no 2, pp. 84-90, 2010.

[115] N. Kaur and A. Khanna, "Structural characterization of borotellurite and alumino-borotellurite glasses," *J. Non. Cryst. Solids*, vol. 404, pp. 116–123, 2014.

[116] M. H. M. Zaid, K. A. Matori, S. H. Abdul Aziz, A. Zakaria, and M. S. M. Ghazali, "Effect of ZnO on the physical properties and optical band gap of soda lime silicate glass," *Int. J. Mol. Sci.*, vol. 13, no. 6, pp. 7550–7558, 2012.

[117] A. Ibrahim and S. K. J. Al-Ani, "Models of optical absorption in amorphous semiconductors at the absorption edge - A review and re-evaluation," *Czechoslov. J. Phys.*, vol. 44, no. 8, pp. 785–797, 1994.

[118] R. P. Sreekanth Chakradhar, K. P. Ramesh, J. L. Rao, and J. Ramakrishna, "Mixed alkali effect in borate glasses—EPR and optical absorption studies in xNa_2O–$(30-x)K_2O$–$70B_2O_3$ glasses doped with Mn^{+2}," *J. Phys. Chem. Solids*, vol. 64, pp. 641–650, 2003.

[119] D. Souri and K. Shomalian, "Band gap determination by absorption spectrum fitting method (ASF) and structural properties of different compositions of (60-x) V_2O_5-$40TeO_2$-xSb_2O_3 glasses," *J. Non. Cryst. Solids*, vol. 355, no. 31–33, pp. 1597–1601, 2009.

[120] M. A. Villegas and J. M. F. Navarro, "Physical and structural properties of glasses in the TeO_2-TiO_2-Nb_2O_5 system," *J. Eur. Ceram. Soc.*, vol. 27, no. 7, pp. 2715–2723, 2007.

[121] D. Singh, K. Singh, G. Singh, Manupriya, S. Mohan, M. Arora, and G. Sharma, "Optical and structural properties of ZnO–PbO–B_2O_3 and ZnO–PbO–B_2O_3–SiO_2 glasses," *J. Phys. Condens. Matter*, vol. 20, no. 7, p. 75228, 2008.

[122] K. Sivakumar, E. Natarajan, and N. Kulasekharan, "Optical Band Gap Studies on Dy^{3+} Doped Boro-Tellurite Glasses," *Springer India*, pp. 447–457, 2012.

[123] Q. Hu, M. W. Fu, and X. R. Zeng, "Thermostability and thermoplastic formability Tm , Yb , Lu) bulk metallic glasses," vol. 64, pp. 301–306, 2014.

[124] C. R. Kesavulu, H. J. Kim, S. W. Lee, J. Kaewkhao, N. Wantana, S. Kothan, and S. Kaewjaeng, "Influence of Er^{3+} ion concentration on optical and photoluminescence properties of Er^{3+}-doped gadolinium-calcium silica borate glasses," *J. Alloys Compd.*, vol. 683, pp. 590–598, 2016.

[125] T. Wei, Y. Tian, C. Tian, X. Jing, J. Zhang, L. Zhang, and S. Xu, "Optical spectroscopy and population behavior between $^4I_{11/2}$ and $^4I_{13/2}$ levels of erbium doped germanate glass," *Opt. Mater. Express*, vol. 4, no. 10, pp. 2150–2165, 2014.

[126] I. Kamma, M. Mbila, K. E. S. Gall, and B. R. Reddy, “Spectroscopic characterization of erbium doped glass ceramic,” *Opt. Mater. Express*, vol. 3, no. 6, pp. 6335–6342, 2013.

[127] P. A. Ryabochkina, N. V Sidorova, S. N. Ushakov, and E. E. Lomonova, “Spectroscopic properties of erbium-doped yttria-stabilised zirconia crystals,” *Quantum Electron.*, vol. 44, no. 2, pp. 135–137, 2014.

[128] F. Huang, X. Liu, Y. Ma, S. Kang, L. Hu, and D. Chen, “Origin of near to middle infrared luminescence and energy transfer process of Er^{3+}/Yb^{3+} co-doped fluorotellurite glasses under different excitations,” *Sci. Rep.*, vol. 5, p. 8233, 2015.

[129] F. Chen, T. Wei, X. Jing, Y. Tian, J. Zhang, and S. Xu, “Investigation of mid-infrared emission characteristics and energy transfer dynamics in Er^{3+} doped oxyfluoride tellurite glass.,” *Sci. Rep.*, vol. 5, p. 10676, 2015.

[130] I. Arul Rayappan and K. Marimuthu, “Luminescence spectra and structure of Er^{3+} doped alkali borate and fluoroborate glasses,” *J. Phys. Chem. Solids*, vol. 74, no. 11, pp. 1570–1577, 2013.

[131] O. Ravi, S. J. Dhoble, B. Ramesh, G. Devarajulu, C. M. Reddy, K. Linganna, G. R. Reddy, and B. D. P. Raju, “NIR fluorescence spectroscopic investigations of Er^{3+}-ions doped borate based tellurium calcium zinc niobium oxide glasses,” *J. Lumin.*, vol. 164, pp. 154–159, 2015.

[132] P. Babu, H. J. Seo, K. H. Jang, R. Balakrishnaiah, C. K. Jayasankar, K. Lim, and V. Lavín, “upconversion properties of Er^{3+}-doped metaphosphate laser glasses,” *America (NY).*, vol. 24, no. 9, pp. 2218–2228, 2007.

[133] M. V Vijaya Kumar, K. Rama Gopal, R. R. Reddy, G. V Lokeswara Reddy, and B. C. Jamalaiah, “Luminescence and gain characteristics of 1.53μm broadband of Er^{3+} in lead telluroborate glasses,” *J. Lumin.*, vol. 142, pp. 128–134, 2013.

[134] K. Selvaraju and K. Marimuthu, “Structural and spectroscopic studies on concentration dependent Er^{3+} doped boro-tellurite glasses,” *J. Lumin.*, vol. 132, no. 5, pp. 1171–1178, 2012.

[135] I. Pal, S. Sanghi, A. Agarwal, and M. P. Aggarwal, “Spectroscopic and structural investigations of Er^{3+} doped zinc bismuth borate glasses,” *Mater. Chem. Phys.*, vol. 133, no. 1, pp. 151–158, 2012.

[136] Y. K. Sharma, S. S. L. Surana, R. K. Singh, and R. P. Dubedi, “Spectral studies of erbium doped soda lime silicate glasses in visible and near infrared regions,” *Opt. Mater. (Amst).*, vol. 29, no. 6, pp. 598–604, 2007.

[137] D. A. Turnbull, B. G. Aitken, and S. G. Bishop, “Broad-band excitation mechanism for photoluminescence in Er-doped $Ge_{25}Ga_{1.7}As_{8.3}S_{65}$ glasses,” *J. Non. Cryst. Solids*, vol. 244, pp. 260–266, 1999.

[138] Q. Chen, H. Wang, and Q. Chen, "Spectroscopic study of high Er and Er/Yb concentration doped photosensitive silicate glasses for integrated optics application," *J. Non. Cryst. Solids*, vol. 391, pp. 43–48, 2014.

[139] A. Jha, S. Shen, and M. Naftaly, "Structural origin of spectral broadening of 1.5-μm emission in Er^{3+}-doped tellurite glasses," *Phys. Rev. B - Condens. Matter Mater. Phys.*, vol. 62, no. 10, pp. 6215–6227, 2000.

[140] Y. Guan, Z. Wei, Y. Huang, R. Maalej, and H. J. Seo, "1.55 μm emission and upconversion luminescence of Er^{3+}-doped strontium borate glasses," *Ceram. Int.*, vol. 39, no. 6, pp. 7023–7027, 2013.