UNIVERSITI PUTRA MALAYSIA

EFFECTS OF INCLUSION OF Gd2O3 MICROPARTICLES AND Gd2O3 NANOPARTICLES ON ELASTIC, LINEAR AND NONLINEAR OPTICAL PROPERTIES OF ZINC BOROTELLURITE GLASSES

CHUA EE VON

FS 2018 10
EFFECTS OF INCLUSION OF Gd₂O₃ MICROPARTICLES AND Gd₂O₃ NANOPARTICLES ON ELASTIC, LINEAR AND NONLINEAR OPTICAL PROPERTIES OF ZINC BOROTELLURITE GLASSES

By

CHUA EE VON

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

November 2017
COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs, and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia
Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

EFFECTS OF INCLUSION OF Gd$_2$O$_3$ MICROPARTICLES AND Gd$_2$O$_3$ NANOPARTICLES ON ELASTIC, LINEAR AND NONLINEAR OPTICAL PROPERTIES OF ZINC BOROTELLURITE GLASSES

By

CHUA EE VON

November 2017

Chairman : Associate Professor Halimah Mohamed Kamari, PhD
Faculty : Science

The purpose of this present work is to study the effect of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs on elastic, linear and nonlinear optical properties of zinc borotellurite glass system. Zinc borotellurite glass system doped with gadolinium oxide (Gd$_2$O$_3$) and gadolinium oxide nanoparticles (Gd$_2$O$_3$ NPs) with chemical formula $\{[(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{70}(\text{ZnO})_{30}\}_{1-x}(\text{RE}_2\text{O}_3)_x$ (where $x = 1.0, 2.0, 3.0, 4.0$ and $5.0$ mol% and $\text{RE}_2\text{O}_3 = \text{Gd}_2\text{O}_3$ and Gd$_2$O$_3$ NPs) were fabricated using conventional melt quenching technique.

XRD results confirmed the amorphousity of the glass samples. The infrared spectra of the glass systems indicate the existence of TeO$_3$, TeO$_4$, BO$_3$ and BO$_4$ vibrational groups. The presence of Gd$_2$O$_3$ NPs was proven from TEM images. The longitudinal ultrasonic velocities vary from 3908 to 4076 m/s and 3883 to 4042 m/s for Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses, respectively while the shear ultrasonic velocities vary from 2222 to 2277 m/s and 2251 to 2282 m/s for Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses, respectively. The observed change in ultrasonic velocities shows that there is a substantial change in the structure of the glass. The elastic moduli (longitudinal modulus (L), shear modulus (G), bulk modulus (K) and Young’s modulus (E)) obtained for Gd$_2$O$_3$ doped zinc borotellurite glass system increase from 55.44 to 81.35 GPa, 18.39 to 25.00 GPa, 30.92 to 48.02 GPa and 46.02 to 63.90 GPa, respectively. In addition, the elastic moduli (L, G, K and E) for Gd$_2$O$_3$ NPs doped zinc borotellurite glasses increase from 55.44 to 79.45 GPa, 18.39 to 26.68 GPa, 30.92 to 43.87 GPa and 46.05 to 66.55 GPa, respectively. The increase elastic moduli indicate that the rigidity of the glass increases. The experimental results showed that the elastic properties system depend on the composition of the glass system and the role of Gd$_2$O$_3$ and Gd$_2$O$_3$ nanoparticles inside the glass network.
The direct and indirect optical band gap energy increases from 3.239 to 3.519 eV and 2.587 to 3.172 eV for Gd\(_2\)O\(_3\) doped zinc borotellurite glasses whereas the direct and indirect optical band gap energy for Gd\(_2\)O\(_3\) NPs doped zinc borotellurite glasses decrease from 3.301 to 2.985 eV and 2.790 to 2.386 eV, respectively. In addition, the refractive index of Gd\(_2\)O\(_3\) doped glasses decrease from 2.518 to 2.352 while an increasing trend from 2.456 to 2.551 is observed in Gd\(_2\)O\(_3\) NPs doped zinc borotellurite glasses. It was found that the optical band gap and refractive index of Gd\(_2\)O\(_3\) doped glasses show opposite behaviour to Gd\(_2\)O\(_3\) NPs doped glass systems. This might be attributed to the presence of nanoparticles having large surface area which form high density states that can serve to trap charge carriers.

The nonlinear refractive index of the glass systems showed self-focusing behaviour and reverse saturable absorption (RSA) or two-photon absorption were observed for nonlinear optical absorption. The values of nonlinear refractive index vary from 0.632 to 0.943 \times 10^{-14} \text{cm}^2/\text{W} and 0.266 to 1.515 \times 10^{-14} \text{cm}^2/\text{W} for Gd\(_2\)O\(_3\) and Gd\(_2\)O\(_3\) NPs doped glass systems, respectively. Moreover, the values of nonlinear absorption coefficient vary from 0.616 to 0.747 cm/GW and 0.660 to 0.729 cm/GW for both Gd\(_2\)O\(_3\) and Gd\(_2\)O\(_3\) NPs doped zinc borotellurite glasses, respectively. The variation of nonlinear optical parameters was due to the formation of TeO\(_4\), the presence of lone pairs electron in TeO\(_4\) and the effect of large Gd\(^{3+}\) ion as well as the reduction in size of bulk materials. The results obtained from z-scan suggested that the presently studied glass systems can be used for design of nonlinear optical materials.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN PERANGKUMAN MIKROZARAH Gd₂O₃ DAN NANOZARAH Gd₂O₃ KE ATAS SIFAT ELASTIK, OPTIK LINEAR DAN OPTIK TIDAK LINEAR BAGI KACA ZINK BOROTELLURIT

Oleh

CHUA EE VON

November 2017

Pengerusi : Profesor Madya Halimah Mohamed Kamari, PhD
Fakulti : Sains

Tujuan kajian ini adalah untuk mengkaji kesan Gd₂O₃ dan nanozarah Gd₂O₃ ke atas sifat elastik, optik linear dan optik tidak linear bagi sistem kaca zink borotellurit. Sistem kaca zink borotellurit didopkan dengan gadolinium oksida (Gd₂O₃) dan nanozarah gadolinium oksida (Gd₂O₃ NPs) bagi formula kimia {[(TeO₂)₇₀(B₂O₃)₃₀]₇₀(ZnO)₃₀}₁₋ₓ(RE₂O₃)ₓ (x = 1.0, 2.0, 3.0, 4.0 and 5.0 mol% dan RE₂O₃ = Gd₂O₃ and Gd₂O₃ NPs) telah difabrikasi dengan menggunakan teknik sepuh lindap.

Ciri amorfus bagi sampel kaca telah disahkan oleh hasil XRD. Spektrum inframerah sistem kaca telah menunjukkan kewujudan kumpulan getaran TeO₃, TeO₄, BO₃ dan BO₄. Kewujudan Gd₂O₃ NPs telah dibuktikan daripada imej TEM. Halaju gelombang membujur berubah daripada 3908 ke 4076 m/s dan 3883 ke 4042 m/s bagi kaca zink borotellurit didop dengan Gd₂O₃ dan Gd₂O₃ NPs, masing-masing, manakala, halaju gelombang ricih berubah daripada 2222 ke 2277 m/s dan 2251 ke 2282 m/s bagi kaca zink borotellurit didop dengan Gd₂O₃ dan Gd₂O₃ NPs, masing-masing. Perubahan yang diperhatikan bagi halaju gelombang menunjukkan bahawa terdapat perubahan dalam struktur kaca. Modulus kenyal (modulus membujur (L), modulus ricih (G), modulus pukal (K) dan modulus Young (E)) bagi kaca zink borotellurit didop dengan Gd₂O₃ meningkat daripada 55.44 ke 81.35 GPa, 18.39 ke 25.00 GPa, 30.92 ke 48.02 GPa dan 46.05 ke 63.90 GPa, masing-masing manakala modulus kenyal (L, G, K and E) bagi kaca zink borotellurit didop dengan Gd₂O₃ NPs meningkat daripada 55.44 ke 79.45 GPa, 18.39 ke 26.68 GPa, 30.92 ke 43.87 GPa dan 46.05 ke 66.55 GPa. Peningkatan modulus kenyal menunjukkan bahawa ketegaran kaca meningkat. Hasil uji kajian menunjukkan bahawa sifat elastik sistem bergantung pada komposisi sistem kaca dan peranan Gd₂O₃ dan Gd₂O₃ nanozarah dalam rangkaian kaca.
Tenaga jurang jalur langsung dan tidak langsung meningkat dari 3.239 ke 3.519 eV dan 2.587 ke 3.172 eV bagi kaca zink borotellurit didop dengan Gd$_2$O$_3$ manakala tenaga jurang jalur langsung dan tidak langsung bagi kaca zink borotellurit terdop dengan Gd$_2$O$_3$ NPs menurun dari 3.301 ke 2.985 eV dan 2.790 ke 2.386 eV, masing-masing. Tambahan pula, indeks pembiasan bagi kaca didop Gd$_2$O$_3$ menurun dari 2.518 ke 2.352 manakala trend peningkatan dari 2.456 ke 2.551 telah dicerapi bagi kaca zink borotellurit didop dengan Gd$_2$O$_3$ NPs. Didapati bahawa jurang jalur optik dan indeks pembiasan bagi kaca didop Gd$_2$O$_3$ menunjukkan hasil bertentangan dari sistem kaca didop Gd$_2$O$_3$ NPs. Ini mungkin disebabkan oleh kehadiran nanozarah yang mempunyai kawasan permukaan yang besar yang membentuk keadaan ketumpatan tinggi yang boleh bertindak sebagai perangkap pembawa cas.

Indeks pembiasan tidak linear sistem kaca telah menunjukkan hasil swafokus dan penyerapan tepu songsang atau penyerapan dua foton telah dicerapi bagi penyerapan optik tidak linear. Nilai indeks pembiasan tidak linear berubah dari 0.632 ke 0.943 x 10$^{-14}$ cm$^2$/W dan 0.266 ke 1.515 x 10$^{-14}$ cm$^2$/W bagi sistem kaca terdop Gd$_2$O$_3$ dan Gd$_2$O$_3$ NPs masing-masing. Malahan, nilai pekali penyerapan tidak linear berubah dari 0.616 ke 0.747 cm/GW dan 0.660 ke 0.729 cm/GW bagi kedua-dua kaca zink borotellurit terdop Gd$_2$O$_3$ dan Gd$_2$O$_3$ NPs masing-masing. Variasi optik parameter tidak linear adalah disebabkan oleh pembentukan TeO$_4$, kehadiran pasangan tunggal elektron dalam TeO$_4$ dan kesan Gd$^{3+}$ ion yang besar serta pengurangan saiz bahan pukal. Hasil ujikaji daripada imbasan-Z mencadangkan bahawa sistem kaca yang diuji kaji ini boleh digunakan sebagai reka bentuk bagi bahan optik tidak linear.
ACKNOWLEDGEMENTS

First of all, I would like to thank God for giving me this opportunity to pursue higher degree. I thank God for leading and guiding me throughout this entire project and giving me the wisdom to complete this thesis. Next, I would like to express my gratitude to all the people that had help me and gave me their pieces of advice while I carried out this project. Thank you for your helps and precious advice.

I would also like to thank and honour my supervisor Associate Professor Dr. Halimah Mohamed Kamari. Thank you for your supervision, advice, guidance, knowledge and your encouragement from the beginning of this project till the completion of this project. I want to personally thank you for your commitment and patience in guiding me throughout this entire journey.

Besides, I would like to extent my gratitude to Professor Dr. Azmi Zakaria and Dr Che Azurahanim Che Abdullah for being my co-supervisor. Thank you for your commitment in guiding and support throughout the process of completing the work.

Furthermore, I would like to express my immense gratitude to my all my lab colleagues for sharing the knowledge, experience, creativity and inspiration.

Last but not least, I would like to express my love and utmost gratitude to both of my grandma, my mom and my dad. Thank you for being so supportive, thank you for your continual support, encouragement and most of all unending love. I would like to specially thank my dad for calling me daily to give me words of encouragement and love. I really appreciate for all you have done in my life. Finally, I would like to say: “I love you mom and I love you dad”. 
I certify that a Thesis Examination Committee has met on 2 November 2017 to conduct the final examination of Chua Ee Von on her thesis entitled "Effects of Inclusion of Gd$_2$O$_3$ Microparticles and Gd$_2$O$_3$ Nanoparticles on Elastic, Linear and Nonlinear Optical Properties of Zinc Borotellurite Glasses" 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.

Members of the Thesis Examination Committee were as follows:

**Hishamuddin bin Zainuddin, PhD**
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

**Abdul Halim bin Shaari, PhD**
Professor
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

**Mohd Nizar bin Hamidon, PhD**
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Yasser Bakr Saddeek Muhammed, PhD**
Professor
Al Azhar University
Egypt
(External Examiner)

---

**NOR AINI AB. SHUKOR, PhD**
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 29 January 2018
This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

**Halimah Mohamed Kamari, PhD**
Associate Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Chairman)

**Azmi Zakaria, PhD**
Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Member)

**Che Azurahanim Che Abdullah, PhD**
Senior Lecturer  
Faculty of Science  
Universiti Putra Malaysia  
(Member)

**ROBIAH BINTI YUNUS, PhD**
Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:
Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: __________________ Date: __________________

Name and Matric No: Chua Ee Von, GS42760
Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ________________________________
Name of Chairman of Supervisory Committee: Associate Professor Dr. Halimah Mohamed Kamari

Signature: ________________________________
Name of Member of Supervisory Committee: Professor Dr. Azmi Zakaria

Signature: ________________________________
Name of Member of Supervisory Committee: Dr. Che Azurahanim Che Abdullah
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td><strong>ABSTRAK</strong></td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>vi</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xvii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxvi</td>
</tr>
</tbody>
</table>

## CHAPTER

1 INTRODUCTION

1.1 Preamble 1
1.2 Problem statements 2
1.3 Scope of study 3
1.4 Research objectives 4
1.5 Hypothesis
  1.5.1 Structural properties 4
  1.5.2 Physical properties 4
  1.5.3 Elastic properties 4
  1.5.4 Linear optical properties 5
  1.5.5 Nonlinear optical properties 5
1.6 Outline of thesis 5

2 LITERATURE REVIEW

2.1 Introduction
  2.1.1 Zinc borotellurite glasses 7
  2.1.2 Gadolinium-doped glass system 8
2.2 Structural properties
  2.2.1 X-ray diffraction (XRD) 9
  2.2.2 Fourier transform infrared (FTIR) spectroscopy 9
  2.2.3 Transmission electron microscopy (TEM) 11
2.3 Physical properties
  2.3.1 Density and molar volume 11
  2.3.2 Others physical parameter 12
2.4 Elastic properties
  2.4.1 Ultrasonic wave velocities 13
  2.4.2 Elastic moduli 14
  2.4.3 Elastic parameters 15
  2.4.4 Theoretical models 16
2.5 Linear optical properties
  2.5.1 Optical absorption spectra 16
  2.5.2 Optical band gap 18
2.5.3 Urbach energy 19
2.5.4 Refractive index 20
2.5.5 Electronic polarizability 20
2.5.6 Oxide ion polarizability 21
2.5.7 Optical basicity 22
2.5.8 Metallization criterion 23

2.6 Nonlinear optical properties 23

3 THEORY 26
3.1 Definition of Glass 26
3.2 Principle of Glass Formation 27
3.3 Structure of Tellurite Glass 28
3.4 Structure of Borate Glass 30
3.5 Elastic Properties of Glass 31
3.5.1 Makishima and Mackenzie Model 34
3.5.2 Rocherulle’s Model 36
3.5.3 Bond Compression Model 38
3.5.4 Ring Deformation Model 40
3.6 Linear Optical Properties 42
3.6.1 Optical Absorption Spectra and Optical Band Gap 42
3.6.2 Refractive Index 44
3.6.3 Electronic Polarizability 46
3.6.4 Oxide Ion Polarizability 48
3.6.5 Optical Basicity 48
3.6.6 Metallization Criterion 49
3.7 Nonlinear Optical Properties 50
3.7.1 Introduction to Z-scan Technique 51
3.7.2 Theoretical Calculation of Z-scan Measurement 54
3.7.2.1 Close aperture z-scan method for measuring nonlinear refractive index 54
3.7.2.2 Open aperture z-scan method for measuring nonlinear absorption coefficient 59

4 MATERIALS AND METHODS 62
4.1 Introduction 62
4.2 Sample Fabrication 62
4.3 Sample Characterization 64
4.3.1 Structural Properties 64
4.3.1.1 X-ray diffraction (XRD) technique 64
4.3.1.2 Fourier transform infrared (FTIR) spectroscopy 65
4.3.1.3 Transmission electron microscopy (TEM) 66
4.3.2 Physical Properties 66
4.3.2.1 Density measurement 66
4.3.2.2 Molar volume calculation 67
4.3.3 Elastic Properties 67
4.3.3.1 Pulse-echo technique 67
4.3.4 Optical Properties 68
5 RESULTS AND DISCUSSION

5.1 Gadolinium oxide and gadolinium oxide nanoparticles zinc borotellurite glass system 71

5.2 Structural properties 72
  5.2.1 X-ray diffraction (XRD) analysis 72
  5.2.2 Fourier Transform Infrared (FTIR) spectroscopy 73
  5.2.3 Transmission electron microscopy (TEM) 80

5.3 Physical properties 81
  5.3.1 Density 81
  5.3.2 Molar volume 84

5.4 Elastic properties 91
  5.4.1 Experimental results 91
    5.4.1.1 Ultrasonic velocities 91
    5.4.1.2 Elastic moduli 96
    5.4.1.3 Other elastic parameters 100
  5.4.2 Theoretical models 107
    5.4.2.1 Makishima-Mackenzie model 108
    5.4.2.2 Rocherul’s model 113
    5.4.2.3 Bond compression and ring deformation model 117
  5.4.3 Comparison between experimental and theoretical elastic moduli 131

5.5 Linear optical properties 134
  5.5.1 Optical absorption spectra 134
  5.5.2 Optical band gap 136
  5.5.3 Urbach energy 144
  5.5.4 Refractive index 145
  5.5.5 Molar refraction and electronic polarizability 148
  5.5.6 Oxide ion polarizability 150
  5.5.7 Optical basicity 155
  5.5.8 Metallization criterion 159

5.6 Nonlinear optical properties 161
  5.6.1 Nonlinear refractive index 161
  5.6.2 Nonlinear optical absorption 166
  5.6.3 Third-order nonlinear susceptibility 172
  5.6.4 Figure of merits 175

6 CONCLUSION AND SUGGESTIONS FOR FUTURE WORKS 176
  6.1 Introduction 176
  6.2 Conclusion 176
  6.3 Suggestions for future works 178
REFERENCES 180
APPENDICES 198
BIODATA OF STUDENT 201
LIST OF PUBLICATIONS 202
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Weight of each chemical components for different mol% of x for 5.0 g</td>
<td>62</td>
</tr>
<tr>
<td>4.2 Weight of each chemical components for different mol% of x for 10.0 g</td>
<td>63</td>
</tr>
<tr>
<td>4.3 Tolerance for each measurement in this work</td>
<td>71</td>
</tr>
<tr>
<td>5.1 Peak position ($x_c$) and amplitude (A) of deconvoluted of FTIR spectra for different compositions of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3)_x$ glass system</td>
<td>77</td>
</tr>
<tr>
<td>5.2 Peak position ($x_c$) and amplitude (A) of deconvoluted of FTIR spectra for different compositions of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glass systems</td>
<td>77</td>
</tr>
<tr>
<td>5.3 Peak position ($x_c$) and amplitude (A) of deconvoluted of FTIR spectra for different compositions of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glass systems</td>
<td>78</td>
</tr>
<tr>
<td>5.4 FTIR assignments of the peaks observed in the deconvoluted FTIR spectra of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses</td>
<td>78</td>
</tr>
<tr>
<td>5.5 Concentrations of structural units presents in ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3)_x$ glass system</td>
<td>80</td>
</tr>
<tr>
<td>5.6 Concentrations of structural units presents in ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glass system</td>
<td>81</td>
</tr>
<tr>
<td>5.7 Density ($\rho$), molar volume ($V_m$), excess volume ($V_e$) and crystalline volume ($V_c$) of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3)_x$ glass systems</td>
<td>87</td>
</tr>
<tr>
<td>5.8 Density ($\rho$), molar volume ($V_m$), excess volume ($V_e$) and crystalline volume ($V_c$) of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glass systems</td>
<td>90</td>
</tr>
<tr>
<td>5.9 Density and molar volume of gadolinium and gadolinium nanoparticles doped glass system and previous studies</td>
<td>92</td>
</tr>
<tr>
<td>5.10 Ultrasonic velocities of ${[(\text{TeO}<em>2)</em>{70}(\text{B}<em>2\text{O}<em>3)</em>{30}]</em>{70}(\text{ZnO})<em>{30}]</em>{1-x}(\text{RE}_2\text{O}_3)_x$ glasses where RE = Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs</td>
<td>95</td>
</tr>
</tbody>
</table>
5.11 Longitudinal and shear ultrasonic velocities of gadolinium oxide and gadolinium oxide nanoparticles doped glass system and previous studies

5.12 Elastic moduli of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.13 Elastic moduli of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3} NPs)\textsubscript{x} glasses

5.14 Elastic moduli of gadolinium oxide and gadolinium oxide nanoparticles doped zinc borotellurite glasses and previous studies

5.15 Debye temperature (\(\theta_D\)) and softening temperature (\(T_s\)) of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.16 Debye temperature (\(\theta_D\)) and softening temperature (\(T_s\)) of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3} NPs)\textsubscript{x} glasses

5.17 Packing density (\(V_t\)), dissociation energy (\(G_t\)) and elastic moduli calculated using Makishima-Mackenzie model of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.18 Packing density (\(V_t\)), dissociation energy (\(G_t\)) and elastic moduli calculated using Makishima-Mackenzie model of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3} NPs)\textsubscript{x} glasses

5.19 Packing density (\(C_t\)), dissociation energy (\(G_t\)) and elastic moduli calculated using Rocherulle model of \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.20 Number of network bonds per unit volume, \(n_b\), stretching force constant, \(F\), atomic ring size, \(\tau\), average cross-link density, \(<n_c>\) and Poisson’s ratio, \(\sigma_{bc}\) calculated based on Bond compression model for \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.21 Number of network bonds per unit volume, \(n_b\), stretching force constant, \(F\), atomic ring size, \(\tau\), average cross-link density, \(<n_c>\) and Poisson’s ratio, \(\sigma_{bc}\) calculated based on Bond compression model for \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses

5.22 Bulk modulus, \(K_{bc}\), ratio of \(K_{bc}/K_e\), shear modulus, \(G_{bc}\), longitudinal modulus, \(L_{bc}\) and Young’s modulus, \(E_{bc}\) calculated based on Bond compression model for \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_{1-x}(Gd\textsubscript{2}O\textsubscript{3})\textsubscript{x} glasses
5.23 Number of network bonds per unit volume, $n_b$, stretching force constant, $F$, atomic ring size, $\ell$, average cross-link density, $<n_c>$ and Poisson’s ratio, $\sigma_{bc}$ calculated based on Bond compression model for $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.24 Bulk modulus, $K_{bc}$, ratio of $K_{bc}/K_e$, shear modulus, $G_{bc}$, longitudinal modulus, $L_{bc}$ and Young’s modulus, $E_{bc}$ calculated based on Bond compression model for $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.25 The comparison between experimental elastic moduli ($G_e, K_e$ and $E_e$), bond compression model ($G_{bc}, K_{bc}$ and $E_{bc}$), Makishima-Mackenzie model ($G_{MM}, K_{MM}$ and $E_{MM}$) and Rocherulle model ($G_{RM}, K_{RM}$ and $E_{RM}$) for shear modulus, bulk modulus and Young’s modulus of $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.26 The comparison between experimental elastic moduli ($G_e, K_e$ and $E_e$), bond compression model ($G_{bc}, K_{bc}$ and $E_{bc}$), Makishima-Mackenzie model ($G_{MM}, K_{MM}$ and $E_{MM}$) and Rocherulle model ($G_{RM}, K_{RM}$ and $E_{RM}$) for shear modulus, bulk modulus and Young’s modulus of $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.27 Cutoff wavelength, $\lambda_{cut}$, Direct optical band gap, $E_{opt}^1$, Indirect optical band gap, $E_{opt}^2$, Urbach energy, $\Delta E$ and refractive index, $n_b$ of Gadolinium oxide Zinc-borotellurite, $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.28 Cutoff wavelength, $\lambda_{cut}$, Direct optical band gap, $E_{opt}^1$, Indirect optical band gap, $E_{opt}^2$, Urbach energy, $\Delta E$ and refractive index, $n_b$ of Gadolinium oxide nanoparticles Zinc-borotellurite, $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses

5.29 Comparative studies between Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses and previous studies

5.30 Comparison between the refractive index of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses and previous reported results

5.31 Molar refraction, $R_m$, electronic polarizability, $\alpha_{el}$, oxide ion polarizability, $\alpha_{O^-}$, optical basicity, $\Lambda$ and metallization criterion, $M$, of gadolinium oxide zinc-borotellurite, $\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3\text{ NPs})_x$ glasses
5.32 Molar refraction, $R_m$, electronic polarizability, $\alpha_m$ and oxide ion polarizability, $\alpha_{O^-}$, optical basicity, $\Lambda$ and metallization criterion, $M$, of gadolinium oxide nanoparticles zinc-borotellurite, $\{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3\text{ NPs})_x$ glasses

5.33 Comparison between the oxide ion polarizability and optical basicity of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses and previous reported results

5.34 Nonlinear refractive index, $n_2$, nonlinear absorption coefficient, $\beta$, third-order nonlinear susceptibility, $\chi^{(3)}$ and figure of merit (FOM) of gadolinium oxide zinc-borotellurite, $\{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x$ glasses

5.35 Nonlinear refractive index, $n_2$, nonlinear absorption coefficient, $\beta$, third-order nonlinear susceptibility, $\chi^{(3)}$ and figure of merit (FOM) of gadolinium oxide nanoparticles zinc-borotellurite, $\{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3\text{ NPs})_x$ glasses

5.36 Nonlinear refractive index and nonlinear absorption coefficient of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses and previous studies
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Structural of TeO4 units (Kalampounias et al., 2011)</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Structural of TeO3 units (Kalampounias et al., 2011)</td>
<td>10</td>
</tr>
<tr>
<td>3.1</td>
<td>Volume and enthalpy changes as a function of temperature associated with cooling and heating of a glass-forming system showing glass transformation range, glass transformation, and fictive temperature (Karmakar et al., 2016)</td>
<td>27</td>
</tr>
<tr>
<td>3.2</td>
<td>Effect of temperature on the rates of nucleation and crystal growth for a glass-forming melts (Karmarkar et al., 2016)</td>
<td>28</td>
</tr>
<tr>
<td>3.3</td>
<td>The classification of the tellurite crystals (El-Mallawany, 2002)</td>
<td>29</td>
</tr>
<tr>
<td>3.4</td>
<td>The types of borate group found in alkali borate glass system: (a) The boroxol group. (b). The pentaborate group. (c) The triborate group. (d) The diborate group (Krogh-Moe, 1965)</td>
<td>31</td>
</tr>
<tr>
<td>3.5</td>
<td>Ring deformation model, ( l = \frac{\text{number of bonds} \times \text{bond length}}{\pi} ) (El-Mallawany, 2002)</td>
<td>32</td>
</tr>
<tr>
<td>3.6</td>
<td>Ring deformation model, ( l = \frac{\text{number of bonds} \times \text{bond length}}{\pi} ) (El-Mallawany, 2002)</td>
<td>41</td>
</tr>
<tr>
<td>3.7</td>
<td>Schematic representation of direct and indirect band gap (Yadav, 2015)</td>
<td>43</td>
</tr>
<tr>
<td>3.8</td>
<td>Example of nonlinear refraction in a z-scan experiment. The curves of normalized transmittance in variation with z coordinate in case of close aperture for nonlinear refractive index measurement of sample CS2: (a) self-focusing (( n_2 &gt; 0 )); (b) self-defocusing (( n_2 &lt; 0 )) (Li, 2017)</td>
<td>53</td>
</tr>
<tr>
<td>3.9</td>
<td>Example of nonlinear absorption in a z-scan experiment. The curves of normalized transmittance variation with z coordinate in case of open aperture for the measurement of nonlinear absorption coefficient: (a) saturable absorption (SA) (( \beta &lt; 0 )); (b) reverse saturable absorption (RSA) (( \beta &gt; 0 )) (Li, 2017)</td>
<td>54</td>
</tr>
<tr>
<td>3.10</td>
<td>( T(z)-z ) curves calculated using z-scan theory when taking ( n_2 &gt; 0 ) and ( n_2 &lt; 0 ) (Li, 2017)</td>
<td>58</td>
</tr>
</tbody>
</table>
4.1 Schematic flow chart for the preparation of Gadolinium and gadolinium NPs Zinc Borotellurite glasses

4.2 Schematic diagram of z-scan measurement setup

5.1 X-ray diffraction (XRD) spectra for gadolinium oxide zinc borotellurite, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3)_x\) glasses

5.2 X-ray diffraction (XRD) patterns for gadolinium oxide nanoparticles zinc borotellurite, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glasses

5.3 FTIR spectra of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3)_x\) glasses

5.4 FTIR spectra of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glasses

5.5 Deconvoluted FTIR spectra of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3)_x\) glass samples with \(x = 5.0\) mol%

5.6 Deconvoluted FTIR spectra of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glass samples with \(x = 5.0\) mol%

5.7 Concentration of TeO\(_4\) and BO\(_4\) structural units in gadolinium zinc borotellurite, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3)_x\) glasses

5.8 Concentration of TeO\(_4\) and BO\(_4\) structural units in gadolinium nanoparticles zinc borotellurite, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glasses

5.9 TEM of gadolinium oxide nanoparticles doped zinc borotellurite, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glass \((x = 3.0\) mol%)

5.10 Density versus concentration of gadolinium oxide and gadolinium oxide nanoparticles zinc borotellurite glasses, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{RE}_2\text{O}_3)_x\) where \(\text{RE}_2\text{O}_3 = \text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3 \text{ NPs}\)

5.11 Field strength of Gd\(^{3+}\) ions versus concentration of gadolinium oxide and gadolinium oxide nanoparticles zinc borotellurite glasses, \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{RE}_2\text{O}_3)_x\) where \(\text{RE}_2\text{O}_3 = \text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3 \text{ NPs}\)

5.12 Density and molar volume of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3)_x\) glass systems

5.13 Density and molar volume of \([(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}]_{\text{ZnO}}_{30}\) \(_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x\) glass systems

xix
5.14 Molar volume of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glass system

5.15 Excess volume of Gd$_2$O$_3$ and Gd$_2$O$_3$ nanoparticles doped zinc borotellurite glass systems

5.16 Molar volume and crystalline volume of TeO$_2$-B$_2$O$_3$-ZnO-Gd$_2$O$_3$ glass system

5.17 Molar volume and crystalline volume of TeO$_2$-B$_2$O$_3$-ZnO-Gd$_2$O$_3$ NPs glass system

5.18 Ultrasonic velocities of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ glasses

5.19 Ultrasonic velocities of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glasses

5.20 Longitudinal ultrasonic velocities of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glasses

5.21 Shear ultrasonic velocities of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glasses

5.22 Elastic moduli for [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ glass system

5.23 Elastic moduli for [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glass system

5.24 Comparison between the experimental elastic moduli of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ and [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glasses

5.25 Poisson’s ratio of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ glass system

5.26 Poisson’s ratio of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glass system

5.27 Debye temperature of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ glasses

5.28 Debye temperature of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$ NPs)$_x$ glasses

5.29 Softening temperature of [{(TeO$_2$)$_{70}$(B$_2$O$_3$)$_{30}$}$_{70}$(ZnO)$_{30}$]$_{1-x}$(Gd$_2$O$_3$)$_x$ glass system
5.30 Softening temperature of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glass system

5.31 Packing density of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.32 Dissociation energy of Gd_2O_3 and Gd_2O_3 NPs doped zinc borotellurite, \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.33 Elastic moduli (Young's modulus, E, bulk modulus, K and shear modulus, G) of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.34 Poisson's ratio of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.35 Packing density of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.36 Dissociation energy of Gd_2O_3 and Gd_2O_3 doped zinc borotellurite, \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.37 Elastic moduli (Young’s modulus, E, bulk modulus, K and shear modulus, G) of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.38 Poisson’s ratio of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) and \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3 \text{ NPs})_{x} \) glasses

5.39 The number of bonds per unit volume of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glasses

5.40 Average stretching force constant of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glasses

5.41 Atomic ring size of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glasses

5.42 Average cross-link density of \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glasses

5.43 Poisson's ratio calculated based on Bond compression model for \( \{(TeO_2)_{70}(B_2O_3)_{30}\}_x(ZnO)_{30}\}_1-x(Gd_2O_3)_{x} \) glasses
5.44 Bulk modulus calculated based on Bond compression model for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

5.45 Ratio of $K_{bc}/K_e$ of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

5.46 Variation of the estimated atomic ring size with the values of $K_{bc}/K_e$ for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

5.47 The number of bonds per unit volume of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.48 Average stretching force constant of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.49 Atomic ring size of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.50 Average cross-link density of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.51 Poisson’s ratio calculated based on Bond compression model for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.52 Bulk modulus calculated based on Bond compression model for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.53 Ratio of $K_{bc}/K_e$ of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.54 Variation of the estimated atomic ring size with the values of $K_{bc}/K_e$ for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.55 UV-visible absorption spectra for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

5.56 UV-visible absorption spectra for \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.57 Absorption coefficient of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

5.58 Absorption coefficient of \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3 NPs)_x glasses

5.59 Graph of direct energy band gap for gadolinium oxide doped zinc borotellurite, \{[(TeO_2)_{70}(B_2O_3)_{30}]_{70}(ZnO)_{30}\}_{1-x}(Gd_2O_3)_x glasses

\textit{xxii}
5.60 Graph of Indirect energy band gap for gadolinium oxide doped zinc borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3})\_x \text{glasses}  

5.61 Graph of direct optical band gap for gadolinium oxide nanoparticles doped zinc borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3} NPs)\_x \text{glasses}  

5.62 Graph of Indirect optical band gap for gadolinium oxide nanoparticles doped zinc borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3} NPs)\_x \text{glasses}  

5.63 Variation of direct and indirect optical band gap energy with glass composition for direct and indirect transition of gadolinium oxide doped zinc borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3})\_x \text{glasses}  

5.64 Variation of direct and indirect optical band gap energy with glass composition for direct and indirect transition of gadolinium oxide nanoparticles doped zinc borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3} NPs)\_x \text{glasses}  

5.65 Comparative direct optical band gap between Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.66 Comparative indirect optical band gap between Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.67 Refractive index of Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.68 Electronic polarizability and oxide ion polarizability of of Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.69 Oxide ion polarizability of Gadolinium oxide Zinc-borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3})\_x \text{glasses}  

5.70 Oxide ion polarizability of Gadolinium nanoparticles oxide Zinc-borotellurite, \{[(TeO\textsubscript{2})\textsubscript{70}(B\textsubscript{2}O\textsubscript{3})\textsubscript{30}]\textsubscript{70}(ZnO)\textsubscript{30}\}_1-x(Gd\textsubscript{2}O\textsubscript{3} NPs)\_x \text{glasses}  

5.71 Comparative studies between the molar refractivity of Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.72 Comparative studies between the electronic polarizability of Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

5.73 Comparative studies between the oxide ion polarizability of Gd\textsubscript{2}O\textsubscript{3} and Gd\textsubscript{2}O\textsubscript{3} NPs doped zinc borotellurite glasses  

xxiii
5.74 Optical basicity of Gadolinium oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

5.75 Optical basicity of Gadolinium nanoparticles oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses

5.76 Comparative studies between the optical basicity of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses

5.77 Metallization criterion of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses

5.78 Z-scan close aperture curves for gadolinium oxide zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

5.79 Z-scan close aperture curves for gadolinium oxide nanoparticles zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses

5.80 Nonlinear refractive index of Gadolinium oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

5.81 Nonlinear refractive index of Gadolinium oxide nanoparticles Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses

5.82 Comparison between nonlinear refractive index of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses

5.83 Z-scan open aperture curves for gadolinium oxide zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

5.84 Z-scan open aperture curves for gadolinium oxide nanoparticles zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses

5.85 Nonlinear absorption coefficient of Gadolinium oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

5.86 Nonlinear absorption coefficient of Gadolinium nanoparticles oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3 \text{ NPs})_x$ glasses

5.87 Comparison between nonlinear absorption coefficient of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs doped zinc borotellurite glasses

5.88 Third-order nonlinear susceptibility of Gadolinium oxide Zinc-borotellurite, $\{[(\text{TeO}_2)_{70} (\text{B}_2\text{O}_3)_{30}]_{70} (\text{ZnO})_{30}\}_{1-x}(\text{Gd}_2\text{O}_3)_x$ glasses

xxiv
5.89 Third-order nonlinear susceptibility of Gadolinium oxide nanoparticles Zinc-borotellurite, \[\{(\text{TeO}_2)_70(\text{B}_2\text{O}_3)_{30}\}_{70}(\text{ZnO})_{30}\}_1.x(\text{Gd}_2\text{O}_3 \text{ NPs})_x\] glasses
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd₂O₃</td>
<td>Gadolinium oxide</td>
<td>-</td>
</tr>
<tr>
<td>Gd₂O₃ NPs</td>
<td>Gadolinium oxide nanoparticles</td>
<td>-</td>
</tr>
<tr>
<td>TeO₂</td>
<td>Tellurium oxide</td>
<td>-</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>Boron oxide</td>
<td>-</td>
</tr>
<tr>
<td>ZnO</td>
<td>Zinc oxide</td>
<td>-</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
<td>-</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared spectroscopy</td>
<td>-</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron microscopy</td>
<td>-</td>
</tr>
<tr>
<td>NBO</td>
<td>Non-bridging oxygen</td>
<td>-</td>
</tr>
<tr>
<td>BO</td>
<td>Bridging oxygen</td>
<td>-</td>
</tr>
<tr>
<td>tbp</td>
<td>Trigonal bipyramids</td>
<td>-</td>
</tr>
<tr>
<td>tp</td>
<td>Trigonal pyramids</td>
<td>-</td>
</tr>
<tr>
<td>OPD</td>
<td>Oxygen packing density</td>
<td>-</td>
</tr>
<tr>
<td>Vₑ</td>
<td>Excess volume</td>
<td>m³/mol</td>
</tr>
<tr>
<td>Vₒ</td>
<td>Oxygen molar volume</td>
<td>m³/mol</td>
</tr>
<tr>
<td>Vₑ</td>
<td>Crystalline volume</td>
<td>m³/mol</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Vₘ</td>
<td>Molar volume</td>
<td>m³/mol</td>
</tr>
<tr>
<td>vₑ</td>
<td>Longitudinal ultrasonic velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>vₛ</td>
<td>Shear ultrasonic velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>L</td>
<td>Longitudinal modulus</td>
<td>GPa</td>
</tr>
<tr>
<td>S/G</td>
<td>Shear modulus</td>
<td>GPa</td>
</tr>
</tbody>
</table>
K
E
σ
νₘ
θ_D
T_s
V_i / C_i
G_r
n_b
l
⟨n_e⟩
x_c
λ_c
α
E_opt
ΔE
n_0
R_m
α_m
α_{o^2-}
Λ
n_2
β
χ^{(3)}

Bulk modulus
Young’s modulus
Poisson’s ratio
Mean ultrasonic velocities
Debye temperature
Softening temperature
Packing density
Dissociation energy
Number of bonds per unit volume
Atomic ring size
Average cross-link density
Peak position
Cut-off wavelength
Absorption coefficient
Optical band gap energy
Urbach energy
Refractive index
Molar refraction
Electronic polarizability
Oxide ion polarizability
Optical basicity
Nonlinear refractive
Nonlinear absorption coefficient
Third order nonlinear susceptibility

GPa
GPa
-
m/s
K
K
-
kJ/cm³
m⁻³
nm
-
cm⁻¹
nm
cm⁻¹
eV
eV
-
cm³/mol
cm³
Å³
-
cm²/W
cm/GW
esu
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOM</td>
<td>Figure of merit</td>
<td>-</td>
</tr>
<tr>
<td>UVB</td>
<td>Ultraviolet broadband light</td>
<td>-</td>
</tr>
<tr>
<td>ESA</td>
<td>Excited state absorption</td>
<td>-</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Preamble

The studies of materials with high optical nonlinearity have attracted the interests of many researcher due to their important application in fabricating nonlinear optical devices for advanced telecommunication system (Nanda et al., 2015b; Said Mahraz et al., 2013; Paz et al., 2016). Thus, it is important to explore the linear and nonlinear optical behaviour of the materials by estimating the parameters such as optical band gap energy, linear and nonlinear refractive index as well as nonlinear absorption coefficient for desired practical applications. The linear and nonlinear optical properties of different type of materials have been investigated and reported. Among these materials, glasses have been widely received due to their range of composition, the variety in shapes, easy and low cost in mass production, fast response time as well as high optical nonlinearities that are important for fabricating photonic devices (Zaman et al., 2016). In addition, glasses can be doped with wide variety of modifiers or dopants such as heavy metals or rare earth oxides to achieve better linear and nonlinear optical properties for desirable practical applications (Nanda et al., 2015b).

Lately, the glasses doped with lanthanide ions have attracted much more attention due to their potential applications in the design of laser, sensors, optical amplifiers, optoelectronics devices, optical switches and many other applications (Zaman et al., 2016; Liang et al., 2014; Said Mahraz et al., 2013). The presence of 4f electrons in rare earth ions can greatly enhance the nonlinear optical properties of the amorphous material. Besides that, rare earth doped glasses have important properties such as thermal resistant, mechanically strong and chemically stable (Marzouk, 2010; Mahani and Marzouk, 2013; Ami Hazlin et al., 2017).

Amongst all the glasses, tellurite and borate glasses have been widely used as host matrix due to their outstanding characteristics which are attractive for specific applications. TeO$_2$ glasses possess high refractive index ($n_0 > 2$), high rare earth ion solubility, wide transparent range, low loss phonon energy and low melting point (Halimah et al., 2017; Ami Hazlin et al., 2017; Aziz et al., 2017; Paz et al., 2016). Furthermore, TeO$_2$ glasses can also be applied as nonlinear optical materials due to their excellent optical properties. On the other hands, B$_2$O$_3$ glass system has low melting point, high transparency, high thermal stability and good solubility of rare earth ions. Borate glasses have potential applications in laser and photonic devices for development of optical technologies (Ami Hazlin et al., 2017; Halimah et al., 2017; Paz et al., 2016; Aziz et al., 2017; Nanda et al., 2015a). Other than that, glasses doped with ZnO are also attractive materials due to their low cost, non-toxicity and non-hygrosopic nature. ZnO can acts either as glass former or as a modifier or both in the vitreous network. The addition of ZnO to borotellurite glass system will produce low rate crystallization, reduce the melting point and improve the glass forming ability.
Gd$_2$O$_3$ is chosen as a dopant for this study because of its high permittivity and wide energy band gap (5.4 eV) along with good thermal stability that make it as a promising material. Gd$_2$O$_3$ has high luminescence efficiency which make it good host material for luminescence application (Maalej et al., 2015; Singh et al., 2015b). The role of Gd$_2$O$_3$ in oxide glasses is of particular interests because it may serve as a network modifier (Mahani and Marzouk, 2013). The addition of Gd$_2$O$_3$ to the glass system will leads to optically more dispersive with higher refractive index. Besides that, the inclusion of Gd$_2$O$_3$ will increase the nonlinear refractive index and third-order susceptibility of the glass system (Marzouk et al., 2013).

Gd$_2$O$_3$ nanoparticles are also used in this study because glasses doped with rare earth oxide nanoparticles have wide range of resonant absorption frequencies and ultrafast response time which are promising materials for all-optical switching devices. Besides that, it can integrate the large third-order nonlinearity of rare earth ions, excellent thermal and chemical stability of the vitreous network, which associate with the surface plasmon resonance (SPR) for the enhancement effect to electric or light field around the nanoparticles. Meanwhile, the addition of rare earth oxide nanoparticles to the glass system can greatly improve the third-order nonlinear optical response of the amorphous material (Zhong et al., 2014; Aziz et al., 2017).

1.2 Problem statements

The search for new material as alternative for nonlinear optical materials has been reported. Nonlinear optical materials are important in the development of optical fibres. The silica optical fibres have been widely used for all optical switching due to their low loss and long interaction length. However, the low value of third-order nonlinear susceptibility, $\chi^{(3)}$, of silica ($\chi^{(3)} = 2.8 \times 10^{-14}$ esu) requires high switching power and a very long length of fibre to achieve appreciable optical switching application (Senthil Murugan et al., 2006). Besides that, silica-based fibres have been deployed due to zero dispersion and low loss at the wavelength of 1.3 $\mu$m which have important impact on telecommunications. Nonetheless, it is difficult to attain efficient gain at 1.3 $\mu$m in silicate glasses. It is suggested that glass hosts with lower characteristics phonon energies are expected to yield an environment with considerably lower non-radiative decay rates, which is more favourable than for 1.3 $\mu$m emission. Thus, by using glass host other than silica glasses can enhance excited-state absorption (ESA) or non-radiative decay and 1.3 $\mu$m devices may be feasible. Hence, a wide range of glass hosts such as silica phosphates and fluorophosphates, sulphides and other chalcogenides glasses have been investigated but had shown generally low performance (Wang et al., 1994).
It is known that tellurite based glasses are potential amorphous materials for the development of photonic materials application. This is because tellurite based glass have good optical switching response, excellent optical nonlinearity, low optical loss, excellent chemical durability and thermal stability (Yousef et al., 2012). Furthermore, it is reported that tellurite glasses have high refractive index (~ 1.8-2.3), large nonlinear refractive index (about 25 times higher than silica based glasses) and low phonon energy (the highest phonon energy about 800 cm$^{-1}$). The high index is desirable for the increment of the local field correction at a rare earth site which lead to large radiative transition probabilities (Wang et al., 1994). In addition, tellurite glasses have low melting points and high solubility to rare earth ions. The addition of rare earth oxide and rare earth oxide nanoparticles to the tellurite based glass systems are able to enhance the optical properties of the glass systems. Gadolinium oxide (Gd$_2$O$_3$) is significant rare-earth element because of its compounds having excellent electric, optical and magnetic properties (Singh et al., 2015b). Besides that, it also has high luminescence efficiency, acts as attractive role as active ions in optical materials and useful for the development of photonic devices. The inclusion of metal nanoparticles into vitreous matrices can also further improve the third-order nonlinear optical response of the glassy material (Zhong et al., 2014).

However, there are limited information on the effect of gadolinium oxide and gadolinium oxide nanoparticles on elastic, linear and nonlinear optical properties. Therefore, the investigation on gadolinium oxide and gadolinium oxide nanoparticles doped zinc borotellurite glass system are still needed since there are limited data such as elastic, linear and nonlinear optical properties to support their future optical applications. Hence, the purpose of this work is to study the effect of gadolinium oxide and gadolinium oxide nanoparticles on elastic, linear and nonlinear optical properties of zinc borotellurite glass system.

1.3 Scope of study

The purpose of the scope of study is to limit the field of study in this work and to obtain specific parameters that are required for the application of nonlinear optic. The scope of the study in this work is limited to structural properties (XRD, FTIR and TEM), physical properties (density and molar volume), elastic properties (experimental elastic moduli and theoretical elastic moduli calculated using Makishima-Mackenzie model, Rocherulle model, bond compression model and ring deformation model), linear optical properties (optical band gap, urbach energy, refractive index, electronic polarizability, oxide ion polarizability, optical basicity and metallization criterion) and nonlinear optical properties (nonlinear refractive index, nonlinear absorption coefficient, third-order nonlinear susceptibility and figure of merit). The elastic, linear and nonlinear optical properties obtained are for required for the application of nonlinear optic material.
1.4 Research objectives

1. To synthesize gadolinium oxide and gadolinium oxide nanoparticles doped zinc borotellurite glass system with chemical formula, \[\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}(1-x)(\text{Gd}_2\text{O}_3)x\} \] and \[\{(\text{TeO}_2)_{70}(\text{B}_2\text{O}_3)_{30}\}(1-x)(\text{Gd}_2\text{O}_3 \text{ NPs})x\}, \text{ where } x = 1.0, 2.0, 3.0, 4.0 \text{ and } 5.0 \text{ mol%} \text{ by using conventional melt-quenching technique.} \]

2. To study the physical and elastic properties of gadolinium oxide and gadolinium oxide nanoparticles doped zinc borotellurite glass system by using pulse-echo technique as well as to correlate and compare the experimental values and calculated theoretical elastic moduli using Makishima-Mackenzie model, Rocherulle model, Bond compression model and ring deformation model.

3. To analyse the effect of gadolinium oxide and gadolinium oxide nanoparticles on linear and nonlinear optical properties of zinc borotellurite glass system.

1.5 Hypothesis

1.5.1 Structural properties

The addition of \(\text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3\ \text{NPs}\) to the glass system does not leads to any distinguishable sharp peak but denote a broad hump implying the characteristic of amorphous materials (Ami Hazlin et al., 2017; Faznny et al., 2017; Kaur et al., 2016).

The expected structural units of the glass system present in the FTIR spectra are \(\text{TeO}_3\), \(\text{TeO}_4\), \(\text{BO}_3\) and \(\text{BO}_4\) (Azlan et al., 2013; Said Mahraz et al., 2013; Rada et al., 2008b).

1.5.2 Physical properties

The density of the glass system is expected to increase with \(\text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3\ \text{NPs}\) content. This is because \(\text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3\ \text{NPs}\) has higher molecular weight as compared to \(\text{TeO}_2\text{-}\text{B}_2\text{O}_3\text{-ZnO}\) (Pavani et al., 2012; Kundu et al., 2014; Veeranna Gowda, 2015).

The molar volume is expected to have the opposite trend to density of the glass system. This is due to the fact that density is inversely proportional to the molar volume (Kaur et al., 2010).

1.5.3 Elastic properties

The elastic moduli of the glass system are expected to increase with \(\text{Gd}_2\text{O}_3\) and \(\text{Gd}_2\text{O}_3\ \text{NPs}\) concentration. This is because the increase in density leads to increase in compactness and rigidity of the glass as well as increasing elastic moduli (Kanappan et al., 2009; Krishna et al., 2008; Yousef et al., 2016; Saddeek et al., 2010b).
1.5.4 Linear optical properties

The addition of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs is expected to enhance the linear optical properties of the glass system. The optical band gap is expected to increase with increasing Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs concentration. This can be attributed to the higher bond energy of Gd-O bond as compared to Te-O bond and B-O bonds which results in higher average bond energy and thus, increasing optical band gap (Luo, 2007; Abdel-Baki et al., 2012).

The addition of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs to zinc borotellurite glass systems will enhance the refractive index. This is due to high polarization of large size Gd$^{3+}$ cations (El-Mallawany et al., 2008).

1.5.5 Nonlinear optical properties

The inclusion of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs into zinc borotellurite glass system is expected to cause increment in the nonlinear refractive index. The nonlinear refractive index is directly proportional to the linear refractive index of the glass system. Hence, the higher value of linear refractive index will result in higher nonlinear refractive index (Nanda et al., 2015b; Chen et al., 2008).

The addition of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs to the glass system will decrease the nonlinear absorption coefficient. This is because the presence of free carriers in the 4f shell transition in Gd$^{3+}$ ions will cause reduction of nonlinear absorption coefficient (Van Stryland and Sheik-Bahae, 1998).

1.6 Outline of thesis

The overall presentation of this thesis consists of the overview of the research work, literature review of different types of glasses related to the current studies, the theoretical description underpinning this work, the fabrication of rare earth oxide (Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs) doped zinc borotellurite glass series, the experimental procedure for each characterization and experimental results taken as well as analysing the effect of Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs on structural characteristic, physical properties, elastic properties, linear and nonlinear optical properties of zinc borotellurite glasses. The thesis is divided into 6 chapters and each chapter is sub-divided into sub-sections.

Chapter 1 gives an overview to the research, a brief introduction of the glass material and rare earth oxide (Gd$_2$O$_3$ and Gd$_2$O$_3$ NPs) used. It also emphasized the core of the research, the problem statement and the research objectives.
Chapter 2 of this thesis gives a brief literature review on tellurite glass system and gadolinium doped glass system. Besides that, the effect of composition on structural, physical, elastic, linear and nonlinear optical properties were reviewed.

Chapter 3 of this thesis highlights the theoretical aspects of this work, including the definition of glass, basic theory of glass formation, the structure of tellurite and borate glasses. Apart from that, the theoretical model used for calculated theoretical elastic moduli such as Makishima-Mackenzie model, Rocherulle’s model, Bond compression model as well as ring deformation model are also included in this chapter. In addition, this chapter also describe briefly the equations and important parameters used to obtained linear and nonlinear optical properties.

Chapter 4 discussed the method used for glass fabrication and the characterization techniques for structural, physical, optical and elastic properties. Conventional melt-quenching technique is used to fabricate glass samples. The structural properties characterization includes X-ray diffraction (XRD), Fourier transform infrared (FTIR) and Transmission electron microscopy (TEM). Pulse-echo technique was employed to obtain the elastic properties characterization. The physical properties characterization involves density measurements and molar volume calculation. UV-Vis spectroscopy and Z-scan technique are used for linear and nonlinear optical properties characterization.

Chapter 5 highlighted the experimental results taken and data analyses for each characterization. The results obtained for structural properties, physical properties, elastic properties, linear and nonlinear optical properties were discussed. The comparative studies between the experimental and theoretical elastic moduli as well as the comparatives studies between the current glass samples and the previous studies were also covered in this chapter.

Chapter 6 summarized the important outcome of the overall research and suggestions of the future studies.
REFERENCES


Kalampounias, A. G., Nasikas, N. K., and Papatheodorou, G. N. (2011). Structural investigations of the xTeO$_2$-(1-x)GeO$_2$ (x=0, 0.2, 0.4, 0.6, 0.8 and 1) tellurite glasses: A composition dependent Raman spectroscopic study. *Journal of Physics and Chemistry of Solids, 72*(9): 1052–1056.


187


195


