THERMOLUMINESCENCE AND OPTICAL CHARACTERISTICS OF LITHIUM POTASSIUM BORATE GLASS FOR RADIATION THERAPY DOSE MEASUREMENT

YASSER S M ALAJERAMI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Physics)

Faculty of Science
Universiti Teknologi Malaysia

JANUARY 2014

I dedicate this work

To Al-AQSA and to the souls of martyrs

To my dear parents

Whose love, kindness, patience and prayer have brought me this far

To my beloved wife
For her love, understanding and support through my endeavor

To my children
Whose presence fills my life with joy

To my siblings
For their endless laughs and tears

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, Most Merciful. Praise to Allah S.W.T, Peace and blessings of Allah upon His Messenger, Muhammad S.A.W, and all his family and companions.

I would like to express my deepest thanks and gratitude **to my supervisor Dr. Suhairul Hashim** UTM-Malaysia, for his keen supervision, initiating and planning this study, great help, and scientific guidance.

I sincerely acknowledge Prof. Ahmad Termizi co-supervisor, UTM-Malaysia, who was generous in his time and efforts and great help in accomplishing this study. I am grateful for his patient and valuable comments.

Also I am grateful to Dr. Wan Muhamad Saridan for his encouragement and valuable support in all stages of my study.

Sincere thanks and appreciations to all my friends in the Physics Department who supported me during my study.

Many thanks to all people who helped me in my study, in particular Mr Muneer Saleh, Mr Basel Khamis, and Mr Mohammed Mosleh.

Last but not least, special thanks to my mother who supported me with patience and forbearance, my wife (Karima) and to my kids Saleh, Iman and Ahmad and my brothers and sisters for their encouragement.

I am similarly grateful to the Nuclear Malaysia Agency and the Oncology Centre of Sultan Ismail Hospital for giving an outstanding help and guidance in the early stage of this project, in particular, Mr. Muneer Saleh, Mr. Hassan, Mr. Hadi, Mr. Taiman, Mr. Bazlie, Madam Nor-Hayti and Mr. Tawfeeq.

ABSTRACT

Radiosensitive glasses of lithium potassium borate (LKB) co-doped with CuO-MgO then with TiO_2-MgO were prepared using melt-quenching technique. Present studies were carried out, seeking to improve upon the thermoluminescence (TL) signal of such glass systems. The overall aim of this thesis was to develop a radiosensitive glass that is suitable for thermoluminescence dosimetry (TLD). A glow curve with single prominent peak was produced at ~220 ^{o}C as a result of dopant activation (CuO/TiO_2). An enhancement of about three times was shown as a result of adding MgO as a co-dopant activator (LKB: 0.1Cu, 0.1Mg and LKB: 0.5Ti, 0.25Mg- mol%). This enhancement was attributed to the ability of magnesium to create extra traps and consequently energy transfer to monovalent Cu^{+} and Ti^{3+} ions. A charge imbalance was predicted in the glass host by the addition of alkaline (Mg^{2+}). Both LKB:Cu,Mg and LKB:Ti,Mg have low Z material (Z_{eff} = 8.55 and 8.89, respectively), good reproducibility and low fading. The prepared glass showed 15 times less sensitive than that of LiF:Mg,Ti (TLD-100), but a promising dose response linearity was achieved over a long span of irradiation doses (up to 10^{3} Gy). The trap parameters, including the order of kinetics (b), activation energy (E) and frequency factor (s) associated with LKB:Cu,Mg were also determined. Furthermore, a *TolAnal* software was used for glow curve deconvolution and analysis for the created peaks. The photoluminescence spectra (emission and excitation) for the prepared samples were studied. As new mixtures, a series of glass characterization and physical properties were discussed. The achieved results promise the use of these compositions in different dosimetric applications, particularly in medical dosimetry and high dose monitoring.

ABSTRAK

Kaca radiosensitif Litium Kalium Borat (LKB) dikodop dengan CuO-MgO, kemudian dengan TiO_2-MgO disediakan menggunakan teknik sepuh lindap. Kajian ini telah dijalankan untuk menambahbaik isyarat luminesens terma sistem kaca. Matlamat keseluruhan tesis ini ialah untuk menghasilkan kaca radiosensitif yang sesuai dalam dosimetri luminesens terma (TLD). Satu lengkung berbara puncak tunggal telah terhasil pada suhu ~220 ^{o}C, kesan daripada pengaktifan dopan (CuO/TiO_2). Peninggian hampir tiga kali ganda turut diperoleh kesan daripada penambahan MgO sebagai pengaktif kodopan (LKB: 0.1Cu, 0.1Mg dan LKB: 0.5Ti, 0.25Mg- mol%). Peninggian ini mungkin disebabkan sifat magnesium yang mempunyai kebolehan untuk menghasilkan perangkap tambahan dan akhirnya berlaku pemindahan tenaga ke ion monovalen Cu^{+} dan Ti^{3+}. Ketakseimbangan cas turut diramalkan dalam kaca induk dengan penambahan alkali (Mg^{2+}). Kedua-dua LKB:Cu,Mg dan LKB:Ti,Mg mempunyai nombor atom rendah bahan Z (masing-masing $Z_{eff} = 8.55$ dan $Z_{eff} = 8.89$), kebolehulangan yang baik dan kepudaran yang rendah. Kaca yang disediakan ini menunjukkan kepekaan 15 kali lebih rendah berbanding LiF:Mg,Ti (TLD-100), tetapi sambutan dos yang linear telah diperoleh untuk penyinaran dalam tempoh yang lama (sehingga 10^{3} Gy). Parameter perangkap, termasuk aturan kinetik (b), tenaga pengaktifan (E) dan faktor frekuensi (s) yang berkait dengan LKB:Cu,Mg turut ditentukan. Tambahan lagi, perisian *TolAnal* digunakan untuk mendapatkan dekonvolusi lengkung berbara dan analisis untuk puncak yang dihasilkan. Spektrum luminesens cahaya (pemancaran dan pengujaan) untuk sampel yang disediakan turut dikaji. Sebagai satu campuran baharu, satu siri pencirian kaca dan sifat fizikal telah dibincangkan. Dapatan yang dicapai menjanjikan penggunaan komposisi kaca ini dalam pelbagai aplikasi dosimetri, khasnya dalam bidang dosimetri perubatan dan pemantauan dos berjulat tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BG	- Band Gap
BOHC	- Boron Oxygen Hole Center
CGCD	- Computerized Glow Curve Deconvolution
DTA	- Differential Thermal Analysis
ECC	- Elemental Correlation Coefficient
EPR	- Electro Paramagnetic Resonance
ESR	- Electro Signal Resonance
FESEM	- Field Emission Scanning Electron Microscope
FOM	- Figure of Merit
FTIR	- Fourier transform infrared spectroscopy
FWHM	- Full Width at Half Maximum
GFA	- Glass Former Ability
GeO_2	- Germanium Dioxide
ICRU	- International Commission of Radiation Units
IR	- Infra-Red
H_3BO_3	- Boric Acid
Kerma	- Kinetic Energy Released in Materials
k_2CO_3	- Potassium Carbonate
$LiBO_2$	- Lithium Meta-borate
LiB_3O_5	- Lithium Triborate
LiF	- Lithium Fluoride
Li_2CO_3	- Lithium Carbonate
$Li_2B_4O_7$:Mn	- Lithium Tetraborate Doped with Manganese
LET	- Linear energy transfer
LINAC	- Linear accelerator

LKB	- Lithium Potassium Borate
MDD	- Minimum Delectable Dose
MgO	- Magnesium Oxide
$MnCl_2$	- Manganese Chloride
MOSFET	- Metal-oxide semiconductor field effect transistor
PC	- Personal Computer
P_2O_5	- Phosphorus Pentoxide
PL	- Photoluminescence
PMT	- Photomultiplier Tube
PPUM	- Pusat Perubatan Universiti Malaya
PTFE	- Polytetrafluoroethylene
RCF	- Read Calibration Factor
RER	- Relative Energy Response
RSD	- Relative Standard Deviation
SEM	- Scanning Electron Microscope
SIH	- Sultan Ismail Hospital
SiO_2	- Silicon Dioxide
SiO_3	- Silicon Trioxide
SSD	- Source Skin Distance
SSDL	- Secondary Standard Dosimeter Lab
TA	- Thermal Analysis
TiO_2	- Titanium Dioxide
TL	- Thermoluminescence
TLD	- Thermoluminescence dosimetery
UV	- Ultra Visible
XRD	- X-Ray Diffraction

LIST OF SYMBOLS

$^{\circ}C$ - Celsius Degree

$^{\circ}F$ - Fahrenheit Degree

$\AA$ - Angstrom

α - Alpha Particle

β - Beta Particle – Heating Rate

γ - Gamma Rays

λ - Wavelength

υ - Frequency

Ʈ - The average life time of an electron in a trap

ΔE - Energy of the photoelectron

(μ_{en}/ρ) - Mass Energy Absorption Coefficient

$\eta(E)$ - The energy dependent prorated to the TL efficiency

σ - Standard Deviation

σ_T/D - The Relative Total Standard Deviation

σ_s - Relative Standard Deviation

ϕ - The Intensity at Time t

λ - Fading Factor

BI - Levels of Band Gap

B^* - The Average TL Background

b -Kinetic Order

c -Velocity of Light

C -Coulomb – Recombination Constant

CB -Conduction Band

CL - Luminogenic Center

D - Absorbed Dose

D_o - The Lowest Detectable Dose
e - Electronic Charge
E - Energy – Activation Energy for Trapped Electron
E_γ - Energy of the Incident Photon
F - Calibration Factor
F - Ground Level
$F(D)$ - Linearity Index
I_m - Maximum Intensity
I_{TL} - Thermoluminescence Intensity
k - Boltzmann Constant
M - Metastable State
$m(t)$ - The centers recombination
N - The total density of traps
$n(t)$ - The concentration of trapped electrons
P - Trap
S - Stopping Power
s - Frequency factor of the electron trap
T - Temperature
Tg - Glass Transition
T_m - Maximum Temperature
$\mathrm{T_g}$ - Glass Transition
$\mathrm{T_c}$ - Crystaline Temperature
$T_{1/2}$ - Half life
VB - Valence Band
Wi - Fraction of The element i
Z - Atomic Number
Z_{eff} - The effective Atomic Number

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Little over a century ago, in November 1895, Wilhelm Conrad Roentgen discovered the X-ray. A few months later, in March 1896, Henri Becquerel described the radioactivity. The use of ionizing radiation has become increasingly frequent and diverse in the later decades. Today the radiation is used in many sectors of medical, industrial, military and research. Ionizing radiation is a type of radiation characterized by its short wavelength and high frequency, and its ability to produce free radicals (ions) when it interacts with matter. It can remove the tightly bound electrons from the shell of the exposed atom, causing the atom to become charged or ionized. This radiation consists of particles (e.g. alpha, beta and neutron) or electromagnetic waves (X-ray and gamma ray) that are energetic enough to cause ionization and severe biological damage when it absorbed by human tissues. Indeed, the high doses of ionizing radiation can cause mutation, cancer, radiation sickness, and death (Eric and Amato, 2006).

Whatever the type of application, it is often necessary to measure the energy deposited per unit mass during the interaction of radiation with the target. The physical quantity characterizing this concept is called the absorbed dose and is expressed in Gray (Gy). The absorbed dose determination is one of the main objectives of all radiation-related studies.

The dosimeter is a device that plays an important role in the mission of radiation protection and radiation therapy treatment. It measures the risk associated with the use of ionizing radiation directly or indirectly in terms of quantities such as the dose equivalent or effective dose. The radiation dosimeters measure or help to evaluate directly or indirectly, the exposure quantities, Kinetic Energy Released in Matter (Kerma), absorbed dose, equivalent dose, and other quantities related to the ionizing radiation. The dose ranges of interest according to the International Commission of Radiation Units (ICRU) recommendations rely on the energy source; for example, nearly (0.01 to 1) mSv for personal dosimeter, (0.1 to 100) mSv for X-ray diagnosis and up to 5 Sv for radiotherapy doses (ICRU, 1998). Nowadays, different types of radiation detectors are available for medical and environmental applications as summarized in Figure 1.1. In the medical field, to obtain a high-performance treatment for tumour cells and more safety for the normal adjacent tissues, the accuracy of the dose delivered to the tumour cells should be within ± 5% (ICRU, 1976).

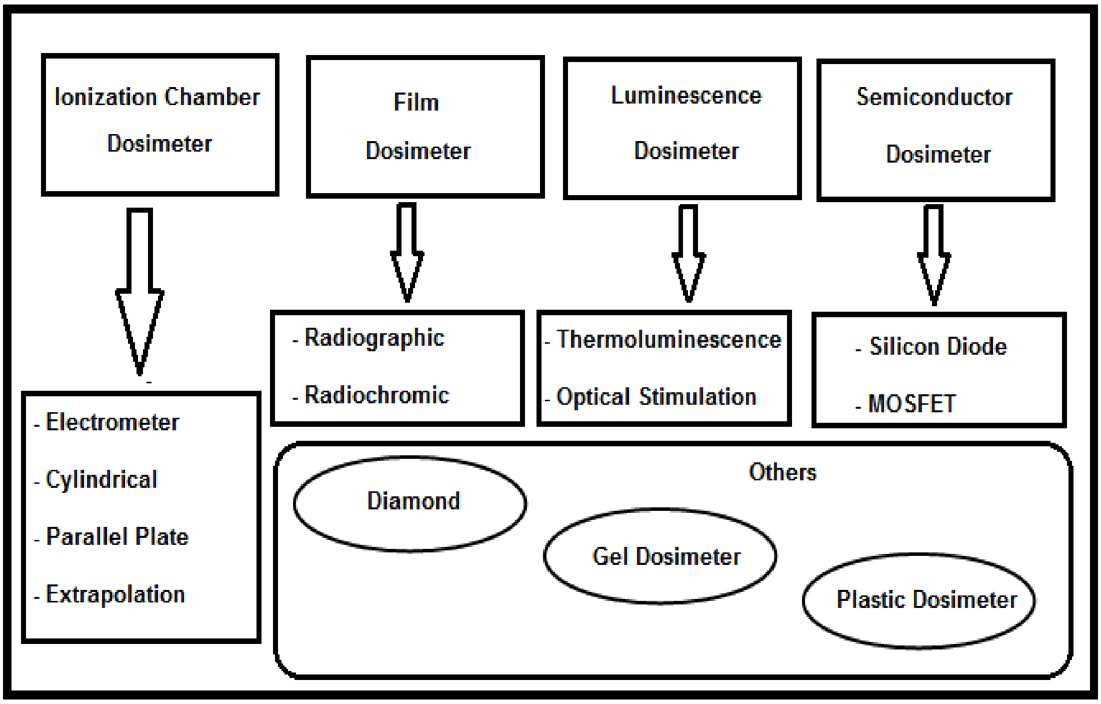

Figure 1.1 The most popular dosimeters for Ionizing Radiation Measurement.

Figure 1.1 illustrates the different types of radiation detectors and measuring used in medical and environmental fields (MOSFET: metal-oxide semiconductor field effect transistor and diamond detectors). Passive dosimetery systems include the dosimeter and readout device. Hence, there will be a delay in obtaining the information. An active dosimeter is the process of direct detection of ionizing radiation for personal and environmental monitoring; i.e., this dosimeter can provide the results immediately i.e. dose and dose rate (Khan, 1994).

1.2 Thermoluminescence Materials

Different types of material with modifiers and dopants can be used in radiation detection. These materials are specified as dosimeters and classified based on its physical and chemical properties to detect the different range of energies. These energies vary, corresponding to the field intended to examine. The TL materials are available in different forms such as hot pressed chips, pellets, powder, impregnated teflon disks. The different shapes of thermoluminescence dosimeter (TLD) can be used in different areas and in particular at critical places.

Furthermore, several admixtures are checked corresponding to the properties of appropriate dosimeters. These dosimeters are considered the most common applied dosimeter particularly in the environmental and medical field. Table 1.1 shows the chemical composition and applications of the TL phosphors.

Table 1.1: The most common TLD used in medical and environmental applications

Material	**Chemical formula**	**Area of interest**	**Reason for choice**
Lithium	LiF:Mg Mg:Ti/Mg,Cu,P	Personal Dosimetery	Tissue-equivalent
Calcium	CaF_2:Dy, $CaSO_4$:Dy	Environmental monitoring	High sensitivity
Lithium borate	$Li_2B_4O_7$:Mn	High dose range dosimetery	High stability
Aluminum	Al_2O_3:C	Medical applications	Simple Peak

1.3 The Energy Transfer

The energy transfer is the physical phenomenon observed when a luminescent molecule in the excited state gives a portion of its excess energy to an acceptor fluorescent molecule. This process is accompanied with emitting of a fluorescence photon. The energy transfer from a donor to an acceptor can be radiative or not. In the case of a non-radiative emission, the energy transfer can also be conducted electronically by phonon vibration or by the collision energy of transferring resonance. These phenomena require the collection of the orbital electrons. Three kinds of thermoluminescence phenomena may occur after the process of heating: radiationless recombination, re-trapping of electron and/or luminescent recombination. The latter can produce a light signal useful for the TLD reader (Yusoff, 2005). The intensity of the emitted light signals is proportional to four main factors depth of trapped electrons, heating used for electron release, chemical tuning between element bonds and types of dopant used.

1.4 Glass and Thermoluminescence

All literature studies confirmed the efficiency of glass in the field of radiation detection and thermoluminescence theory. Several materials can be used in order to synthesize pure glasses such as silicon glass (SiO_2), boron glass (B_2O_3), phosphorus glass (P_2O_5) and germanium glass (GeO_2). The present study focuses on the glass formation by using the boron oxide as a host. Schulman, Kirk, and West's were the first whom prepared the glass by melting a mixture of lithium carbonate (Li_2CO_3) and boric acid (H_3BO_3) then cooled to the room temperature. This method is known as the conventional chemical quenching technique. The Li_2CO_3 and H_3BO_3 are mixed with a few amount of SiO_3 or $MnCl_2$ under the melting point of borate, and then annealed for three hours under the transition temperature of the host. Finally, the mixture was dried for 12 hours at room temperature (Schulman *et al.*, 1965).

1.5 Lithium Borate

The phosphor dosimeter is the most widely used and sensitive dosimeter used in medical and environmental applications. This is attributed to many promising reasons, i.e. the effective atomic number (close to human tissue), sensitivity to a wide range of energy, energy response (stability and consistency), dose dependence linearity and low fading. Many TLDs are commercially available, but the most common types are LiF doped with Mg,Ti and LiF doped with Mg,Cu, or P. Besides, these attractive properties, there are several drawbacks on these dosimeters. For instance, hygroscopic defect and poor spatial resolution up to a few millimeters per spot are the common weakness (McKeever and Moscovitch, 2003). Due to these obstacles, numerous researches have been carried to overcome these drawbacks and to improve the TL properties. Lithium borate dosimeters (tetraborate $Li_2B_4O_7$ and triborate LiB_3O_5) show promising TL properties that passed the disturbance of phosphors and give opulence applications in both medical and environmental fields. Because of its close human tissue absorption coefficient, borate glasses are widely used as a thermoluminescence dosimeter in medical applications and personal monitoring. In addition, its high availability and low manufacturing cost gave this dosimeter the preferences over the other phosphors (Depci *et al*., 2008 and Pekpak *et al*., 2010).

The attractive chemical, physical and optical properties of lithium borates open the gates to enhancing the TLD efficiency. Lithium borate is used as a surface acoustic wave to improve the electrical circuits (Bui *et al*., 2009). As well as, the utilizing of lithium borate as a piezoelectric and pressure probe gave high promising results (Bui *et al*., 2009). Lithium tetraborate ($Li_2B_4O_7$) doped with manganese was the first lithium borate dosimeter; this older effort showed a low TL sensitivity. This drawback is attributed to the incompatibility between the region of trapped electron emission (600 nm) and the photomultiplier tube sensitivity of the TLD reader (Prokie, 2002).

According to Takenaga *et al*., (1980) and Soramasu *et al*., (1996), the TL emission of lithium borate was reduced to 360 nm by replacing the manganese with copper activator. This shifting makes the wavelength of the emitted light compatible with the photomultiplier tube (PMT) of the TLD-reader. A recent study showed the possibility of using lithium borate to convert the ultraviolet frequency to laser (Eggins, 2003). Countless studies confirmed the efficiency of lithium borate as ionizing radiation detector. The results illustrate a variation showing the dosimetric properties (sensitivity, dose dependence, energy response, fading and reproducibility) to corresponding to the type of dopant and modifier materials added to the borate host. According to Furetta *et al*., (2001a), the lithium borate glow curve shows two different separated glow peaks. Figure 1.2 demonstrates the glow curve that forms a schematic spectrum to identify the relation between the heat treatment (with electrons trapped in the space between the valence and conducting area) and the intensity of TLD signals.

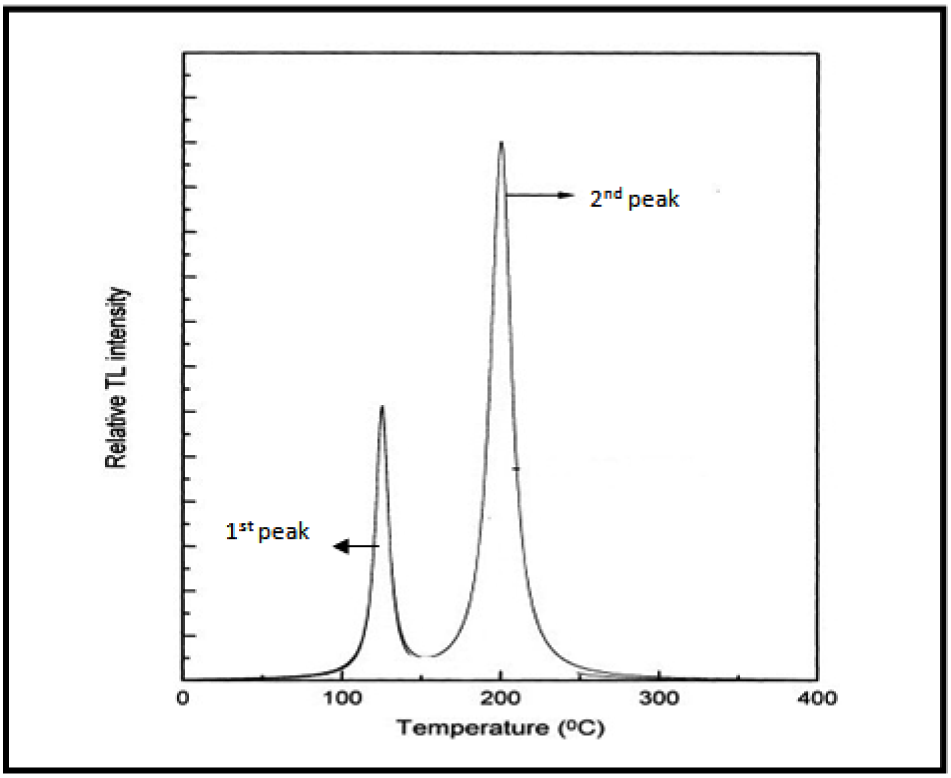

Figure 1.2 The two peaks produce in the TLD reader as a result of thermal induction of Lithium Borate (Furetta, 2001a).

According to Figure 1.2, the lithium borate creates two separated peaks; the first peak appeared at 125°C and the second peak at 200 °C. The first peak fades (disappeared) after 24 hours of irradiation. The supersaturating state occurred at 1 Gy and 10^3 Gy for the first and second peak, respectively (Furetta *et al.*, 2001a). Attractive results were obtained after the activation of lithium bromide lattice with copper (Cu) and indium (In) co-dopant. The main achievement is enhancing of the dose linearity up to 10^3 Gy, and reduce annealing time and temperature to half compared with that applied in the case of lithium fluoride dosimeter (LiF: Mg, Ti). The same study indicated the importance of adding silicon dioxide to overcome the humidity defect and enhance the sensitivity of the TL dosimeter (Furetta, 2001b).

The results of the Park's experiment displayed another aspect related to the dopants effect on the linearity and superlinearity response of Lithium Borate (Park *et al.*, 2002). Three dopants manganese, copper and magnesium were used to activate lithium tetraborate. Copper dopant exhibited superlinearity up to 100 Gy and 10 Gy for manganese dopant (Park *et al.*, 2002). Based on the work of Gorelik and his colleagues, three stable mixtures of Lithium (Li_2O) with borate (B_2O_3) can be used as TLD: lithium tetraborate ($Li_2B_4O_7$), lithium triborate ($Li_2B_3O_5$) and lithium meta-borate ($LiBO_2$) (Gorelik *et al.*, 2003). In more details, the basic compounds in the form of borate crystals are: simple trigonal $(BO_3)^{-3}$, tetrahedral $(BO_4)^{-5}$ groups, bitrigonal $(B_2O_5)^{-4}$ and ditetrahedral $(B_2O_7)^{-8}$ groups, groups with circular 6-membered mixed coordination $(B_3O_6)^{-3}$, $(B_3O_7)^{-5}$, $(B_3O_8)^{-7}$, and $(B_3O_9)^{-9}$ and coupled double 6-membered rings $(B_5O_{10})^{-5}$ (Gorelik *et al.*, 2003). Three main stable compounds in the Li_2O-B_2O_3 system can be generated in the form of crystal, sintered pellets and glass. As a crystal and glass form, they can be divided into lithium meta-borate ($LiBO_2$), lithium tetraborate ($Li_2B_4O_7$), and lithium triborate (LiB_3O_5) as shown in Table 1.2.

Table 1.2: The main chemical properties of Lithium-Borate (Pekpak *et al.*, 2009)

	Lithium Metaborate	**Lithium Triborate**	**Lithium Tetraborate**
Chemical Formula	$LiBO_2$	$Li_2B_3O_5$	$Li_2B_4O_7$
Molecular weight	49.751 g mol^{-1}	119.372 g mol^{-1}	169.123 g mol^{-1}
Phase	Solid	Solid	Solid
Melting Point	845 °C	834 °C	820 °C
Density	2.223 g cm^{-3}	2.747 g cm^{-3}	0.251 g cm^{-3}
Solubility	Soluble in water	Soluble in water	Soluble in water

1.6 Optical Properties

The physical and optical properties of borate glasses and crystals have attracted great interest among the researches. The lithium borate glass has numerous applications in the optical field, particularly on the nonlinear optical phenomena. The interest in lithium borate glass is attributed to its high transparency, thermal stability, ease preparation and good hosting for dopants. Recently, many studies have been done to explore the behavior of lithium borate, either pure or doped with different transition metals or rare-earth elements (Lakshminarayana and Buddhudu, 2006; Elfayoumi *et al.*, 2010 and Padlyak *et al.*, 2010a).

The incorporation of lithium borate in the optical fields has paved the way in ultraviolet and visible laser applications. It has been remarked that the position and intensity of absorption and emission transition bands are highly affected by the type of dopant and its concentrations. Furthermore, lithium borate glasses have shown high stability. This stability improves the laser properties which have different applications in the computing and telecommunication system.

1.7 Problem Statement

This study encompasses investigation of the performance of a TLD detector named LKB co-doped with CuO/MgO and TiO_2/MgO. In general, this study will investigate these dosimeters in terms of their preparation, characterization, optical and thermoluminescence properties.

The luminescence studies of undoped and doped borate dosimeters are started in 1965 by Schulman (Schulman *et al.*, 1965). The dosimeter was in the form of crystal and doped with manganese ($Li_2B_4O_7$:Mn). Although the desired properties were achieved, particularly its effective atomic number but it has low radiation sensitivity. This drawback was attributed to the incompatibility between the wavelength of the emitted light (600 nm) and the photomultiplier tube response region of the TLD's reader. The sensitivity was improved using copper as an activator instead of manganese, which shifted the red-light emission (600 nm) to the blue-light emission (Takenaga *et al.*, 1980). Indeed, the emitted light with 360 nm wavelength (blue emission spectra) enhanced the sensitivity more than ten times, and overcome the sensitivity drawback (Takenaga *et al.*, 1980). Since then, numerous studies were carried to improve the borate glass features, in terms of its preparation, modifier and activator modifications.

According to the literature studies, the preparation modifications were conducted around three types; the single crystal (Park *et al.*, 2003; Rojas *et al.*, 2006; Xiong *et al.*, 2011), the polycrystalline (Prokic, 2001, Prokic, 2002; Sangeeta *et al*., 2004 and Pagonis *et al*., 2006) and the glass system (Pontuschka *et al.*, 2001; Venkateswara *et al.*, 2002; Rojas *et al.*, 2006). For modifiers, several alkali/alkaline metals were used as modifiers to strengthen the relative stability of borate glass (Srivastava and Supe, 1989; Martini *et al.*, 1995; Rey, 2003; Manam and Sharma, 2004; Rojas *et al.*, 2006). Regarding to the activators, a variety of dopants and co-dopants either transition metals (Prokic, 2002; Xiong *et al.*, 2011, Elkholy, 2010) or rare earths (Prokic, 2001; Li *et al*., 2005 and Madhukumar *et al*., 2007) were added to the host in order to enhance the luminescence. This enhancement based on the consideration of amendments the electron's transition and/or increasing the traps centre. However, the continuous increase of copper and titanium oxide has led to an adverse effect on the TL response (the quenching state). One of the ways is to increase the response by the addition of another impurity (co-dopant), which acts as a charge compensator like P or Mg on either Li or K sites. Therefore, the present research aims are to evaluate the thermoluminescent properties of LKB doped with CuO and TiO_2, and the efficiency of MgO as co-dopant on the optical and thermal stimulation properties.

In the current study, a new glass dosimeter based on borate host will be prepared. The host is strengthened by two alkali modifiers (lithium and potassium), and its luminescence effects will be enhanced by the presence of co-dopant (CuO with MgO and TiO_2 with MgO). The optical and thermoluminescent properties of these samples will be reported for the first time.

1.8 Objectives of the Study

The objectives of this study are:

1. To examine the optical properties (i.e., Photoluminescence, Absorption, Reflection and Refractive index etc) of the new TL glass dosimeters (LKB:CuO,Mg and LKB:TiO_2,Mg).

2. To describe the fundamental dosimetric properties of the new TL glass dosimeters (i.e., reproducibility, dose linearity, sensitivity, minimum detectable dose, fading and effective atomic number etc).

3. To determine the luminescence dependency of borate glass with the presence of modifiers, dopant and co-dopant.

4. To compare the performances of the glass dosimeters (LKB:CuO-MgO and LKB:TiO_2-MgO) with different co-dopant concentrations.

Schematic representation of the Problem Statement of the current study:

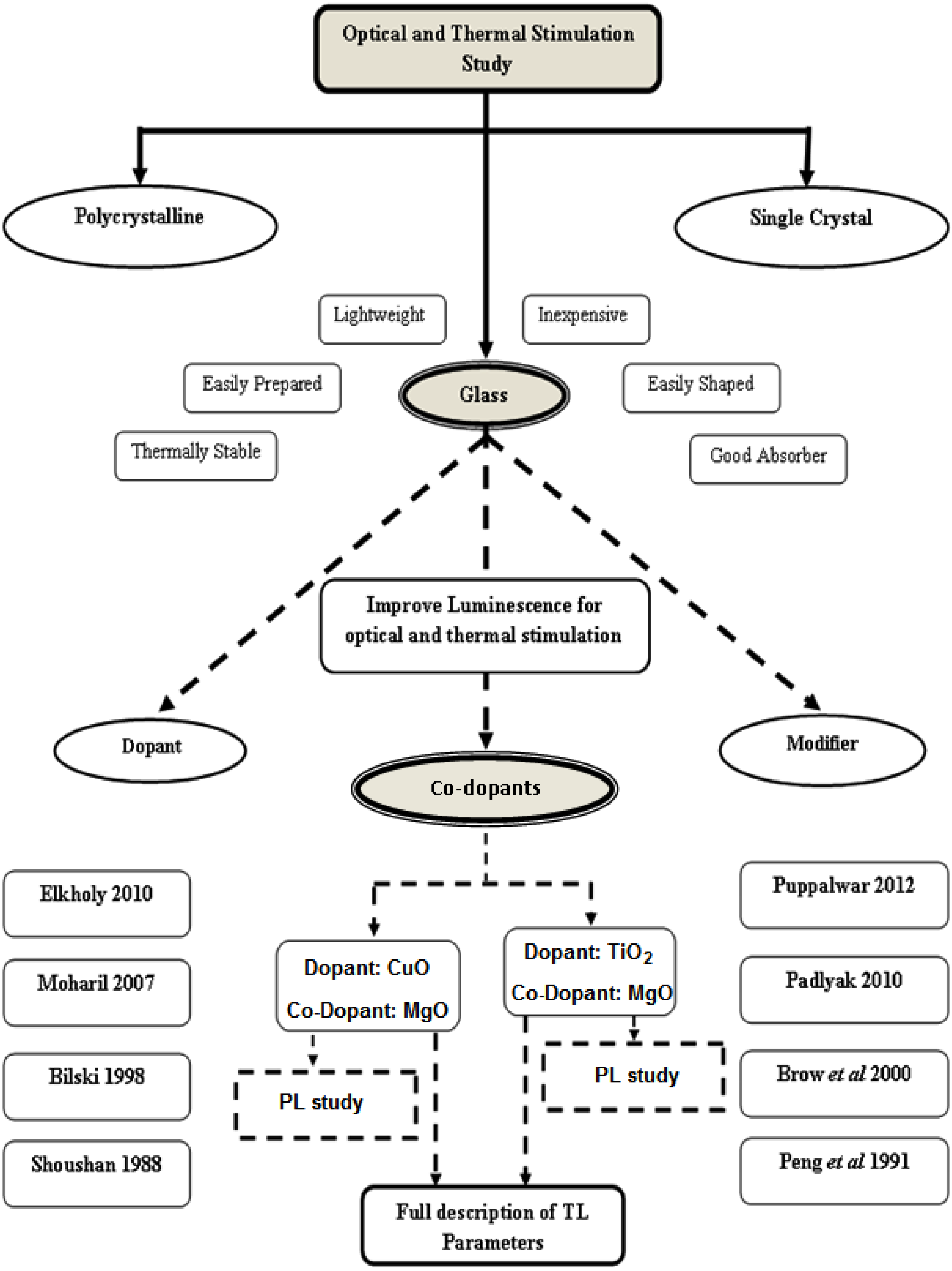

Figure 1.3 Schematic representations for the problem statement of the current study.

1.9 Scope of the Thesis

In regard to this doctoral thesis, the thesis is organised to five chapters. Chapter 1 presents the background, problem statement, objectives and contributions of the research. In addition, this chapter summarizes the importance of choosing the new glass dosimeters.

Literature review is presented in Chapter 2. It provides a brief description on the basis of the general information about borate compounds and glass formations, and full overview of optical properties, thermoluminescence phenomena and TL parameters. In addition, the theoretical equation needs to be used in order to obtain more information based on the glow curve (kinetic energy parameters: activation energy, frequency factor and degree of binding energy). This chapter also involves the physical and chemical concepts related to the dosimetric properties. For instance, dose rate effect, annealing condition, energy dependence, glow curve parameters, relative energy response and reproducibility.

Chapter 3 describes the instrumentations and methods used during the research to get the results and to accomplish the project. These instruments are divided into characterization analysis (XRD, FTIR, FESEM, and DTA), optical properties (PL and UV-VIS-NIR spectrophotometer) and thermoluminescence studies (Ionizing radiation sources and TLD-reader) machines.

Chapter 4 provides the results obtained from the glass composition. This chapter is divided into three sections; the first part describes the characterization of the new prepared samples. The later explain the optical and the thermoluminescence properties of the new compositions. In more details, the results obtained are discussed in depth and the comparison being made.

Finally, Chapter 5 summarizes the main findings achieved through this research, and suggests several recommendations for future studies.

REFERENCES

Abdel-Rahim, M.A., El-Korashy, A., Hafiz, M.M., Mahmoud, A.Z. (2008). Kinetic study of non-isothermal crystallization of BixSe100-x. *Physica B.* 403, 2956-2959.

Aboud, H., Wagiran, H., Hossain, I., Hussin. R. (2012). Infrared Spectra and Energy band gap of Potassium Lithium Borate glass dosimetry, *Int J Phys. Sci.* 7(6), 929-226.

Aitken, M.J. (1974). *Physics and Archaeology*. 2nd edn, Oxford University Press, Oxford.

Alajerami, S.M.Y., Hashim, S., Ramli, A.T., Saleh, M.A., Abdul Kadir, A.B., Saripan, M.I. Dosimetric Characteristics of LKB:Cu,Mg Solid Thermoluminescence Detector *CHIN. PHYS. LETT.* 30(1), (2013a) 017801.

Alajerami, S.M.Y., Hashim, S., Ramli, A.T., Saleh, M.A., Kadni, T. (2012c). Thermoluminescence properties of Li2co3–k2co3–h3bo3 glass system co-doped With CuO and MgO. *Radiat. Prot. Dosim.* 155(1), 1-10.

Alajerami, Y., Hashim, S., Saridan, W. and Ramli, A. T. (2012a). The effect of CuO and MgO impurities on the optical properties of lithium potassium borate glass. *Phys. B.* 407, 2390–2397.

Alajerami, Y., Hashim, S., Saridan, W., Ramli, A. (2012b). The effect of titanium oxide on the optical properties of lithium potassium borate glass. *J Mol Strut.* 1026, 159–167.

Alajerami, Y., Hashim, S., Saridan, W., Ramli, A. (2012d). The effect of phosphorus and copper oxide on the photoluminescence characteristics of Li_2CO_3-K_2CO_3-H_3BO_3 glass. *International Journal of Modern Physics B.* 26, 1-13.

Alajerami, Y., Hashim, S., Saridan, W., Ramli, A. (2013d). The Effect of MgO on the Optical Properties of Lithium Sodium Borate Doped with Cu^+ Ions. *Optics and Spectroscopy*. 114(4), 537-543.

Alajerami, Y., Hashim, S., Saridan, W., Ramli, A., Kasim, A. (2012e). Optical properties of lithium magnesium borate glasses doped with Dy^{3+} and Sm^{3+} ions. *Physica B*. 407, (2012e) 2398–2403

Alajerami, Y., Hashim, S., Ramli, A.T., Saleh, M. I. Saripan, K. Alzimami and Ngie Min Ung. (2013b). *Apllied Radiation and Isotopes*. 78, 21-25.

Alajerami, Y., Hashim, S., Ramli, A.T., Saleh, M. I. Kadri T.. (2013c). *Journal ofLuminescence1*. 43, 1–4.

Alajerami, Y., Hashim, S., Ramli, A.T., Kadri T., Ghoshal, S.K., Ramli, A.T., Saleh, M.A., Ibrahim, Z., Kadni, T., Bradley, D.A. (2013e). Luminescence characteristics of Li_2CO_3–K_2CO_3–H_3BO_3 glasses co-doped with TiO_2/MgO. *Applied Radiation and Isotopes*. 82, 12–19.

Ali, A.A. (2009). Optical properties of Sm^{3+}-doped CaF_2 bismuth borate glasses. *J. Lumin.* 129 (11), 1314-1317.

Allen, A.H., Tankard and Arnold R. (1904). The determination of boric acid in cider, fruits. *Analyst* 29: 301.

Almeida, A.F.L., Thomazini, D., Sombra A.S.B. Inglaterra. (2001). Structural studies of lithium triborate (LBO–Li_3BO_5)in borophosphate glass-ceramics. *Int. J. Inorg. Mater.* 3, 829-838.

Anishia, S.R., Jose, M.T., Annalakshmi, O., Ponnusamy and Ramasamy, V. (2010). *Journal of Luminescence,* 130, 1834-1840.

Attix. F.H. (1968). Basic gamma ray dosimetery. *Health Phys*. 15(1), 49-53.

Atul, D. Sontakke, Anal, T., Kaushik, B., Annapurna, K. (2009). *Physica B*. 404, 3525-3529.

Azman, K. (2010). *Physical and optical properties of neodymium doped and neodymium/erb ium co-doped tellurite glass system.* PhD. Thesis. Universiti Teknologi Malaysia, Skudai.

Balaji Rao, R., Krishna Rao, D., Veeraiah, N. (2004). The role of titanium ions on structural, dielectric and optical properties. *Material Chemistry Physics,* 87, 357–369.

Balaji, R., Naga Raju G., Veeraiah, N. (2005). *Indian J Pure AP Material,* 43, 192-202.

Balaji, R., Rosario, A., Gerhardt, Veeraiah, N. (2008). *Journal of Physics and Chemistry of Solids,* 69(11), 2813-2826.

Balarin, M. (1979). Half-width and Asymmetry of Glow Peaks and Their Consistent Analytical Representation. *Physical Status Solidi,* 17, 390-399.

Bilski, P. (2002). Lithium fluoride: from LiF:Mg,Ti to LiF:Mg,Cu,P. Radiation Protection Dosimetery. 100, 199–206.

Bilski, P., Budzanowski, M., Olko, P., (1996). A systematic evaluation of the dependence of glow curve structure on the concentration of dopants in LiF:Mg,Cu,P, *Radiation Protection Dosimetery,* 65(1–4), 195–198.

Bilski, P., Budzanowski, M., Olko, P., (1997). Dependence of LiF:Mg,Cu,P (MCP-N) glow-curve structure on dopant composition and thermal treatment. *Radiation Protection Dosimetery*, 69, 187–198.

Bilski, P., Budzanowski, M., Olko, P., Waligorski, M.P.R., (1998). Influence of concentration of magnesium on the dose response and LET-dependence of TL efficiency in LiF:Mg,Cu,P (MCP-N) detectors. *Radiation Protection Dosimetery*, 29, 355–359.

Bos, A.J.J. (2007). Theory of thermoluminescence. *Radiation Measurements,* 41, S45–S56.

Braunilich,P. (1967). Comment on the initial rise method for determining trap depths, *J. Appl. Phys*. 38 (6), 2516 - 2519.

Braunlich, P. and Scharmann, A. (1964). The analysis of Thermoluminescence, *Z. Physics,* 177, 320-322.

Bui, T. H., Bui M. L., Quang V. X., Huynh K. H., Doan P. T., Vinh H. and Tran N. (2009). Growth and luminescent properties of $Li_2B_4O_7$ single crystal doped with Cu, *Journal of Physics*, 187, 1-5.

Burkhardt, B., Piesh, E. (1980). Reproducibility of TLD systems: A comparison Study. *Nuclear Instrument and Methods,* 175**,** 159.

Cameron, J.R., Suntharalingam, N., Kenney, G.K. (1968). *Thermoluminescent Dosimetery*, University of Wisconsin Press, Madison, WI.

Can, N., Karali, T., Townsend, P.D., Vildiz, F., (2006). TL and EPR studies of Cu, Ag and P doped $Li_2B_4O_7$ phosphor, *Journal of Physics D: Applied Physics,* 39, 2038-2043.

Chen, R. (1969). Cathodic Behavior of Alkali Manganese Oxides from Permanganate. *Journal of Electrochemical Society*, 116, 1254-1260.

Chen, R. (1984). In: Horowitz, Y.S. (1st edition). *Thermoluminescent and Thermoluminescent Dosimetery,* CRC Press: Boca Raton, FL.

Chen, R., and Kirsh.Y. (1981*). Analysis of thermally stimulated processes*. Pergamon Press. Oxford. P.85.

Chen, R., and Winer, S.A.A. (1970). Effects of Various Heating Rates on Glow Curves. *Journal of Applied Physics*. 41 (13), 5227-5232.

Chen, T.C., Stoebe, T.G. (1998). Influence of annealing on kinetic trapping parameters in LiF:Mg,Cu,P thermoluminescent phosphors. *Radiation Measurements,* 29(1), 39–44.

Chung, K. S., Park, C. Y., Lee, J. I. Kim, J. L. (2010). Development of a new curve deconvolution algorithm for optically stimulated luminescence *Radiat. Meas*. 45, 320-325.

Clavaguera-Mora, M.T. (1995). Glassy materials: thermodynamic and kinetic quantities. *Journal of Alloys and Ccompounds,* 220(1-2), 197-205.

Cuong, T.T., Dung, P.T., Hain, Q., Ha, V.T., Hung, N.M., Khoi, N.T. Ku, N.X.,Quang, V.X., Thanh, N.T., Than, N.Q. (2004). In Proc., The Ninth Asia Pacific Physics Conference. Hanoi, Vietnam.

Daniels, F., Boyd, C.A. & Saunders, D.F. (1953). Thermoluminescence as a Research Tool.

David, M., Sunta, C.M., Ganguly, A.K. (1977). Thermoluminescence of quartz: Part I – Glow curve & Spectral characteristics. *Indian Journal of Pure & Applied Physics*, 15 (3), 201-204.

Depçi, T., Özbayoglu, G., Yolmaz, A., Yazici, N. (2008). The thermoluminescent properties of lithium triborate. *Nuclear Instrument and Methods*, 266, 755-762.

Dhoble SJ, Gedam SC, Nagpure IM, and Mohril SV. (2008). Luminescence of Cu^+ in halosulphate phosphor. *Journal of Material Science*, 43, 3189–96.

Ege, A., Ekdal, E., Karali, T., Can, N. (2007). Determination of thermoluminescence kinetic parameters of $Li_2B_4O_7$: Cu, Ag, P. Radiation Measurements 42, 1280–1284.

Eggins, S.M. (2003). Laser Ablation ICP-MS Analysis of Geological Materials Prepared as Lithium Borate Glasses. *The Journal of Geostandards and Geoanalysis*, 27 (2), 147-162.

El-Faramawya N A, El-Kameesya S U, El-Agramy A, (2000). The dosimetric properties of in-house prepared copper doped lithium borate examined using the TL-technique. *Radiation Physics and Chemistry,* 58, 9－13.

Elfayoumi M.A.K., Farouk, M., Brik, M.G. Elokr. M.M. (2010). Spectroscopic studies of Sm3+ and Eu3+ co-doped lithium borate glass. *Journal of Alloys and Compounds,* 492, 712–716.

Elkholy, MM. (2010). Thermoluminescence of B2O3–Li2O glass system doped with MgO. *Journal of Luminescence,* 130, 1880–1892.

Elliot, S. R. (1984). *Physics of Amorphous Materials*. Longman group ltd. London, New York.

Eric, J.H. and Amato J.G. (2006). *Radiobiology for the Radiologist*. 6th edition. Philadelphia, USA: Lippinco Hwillians and Wilkins.

Fernandes, A. C., Osvay, M., Santose, J.P., Holovey, V., Ignatovych, M. TL properties of newly developed lithium tetraborate single crystals. *Radiat. Meas.* 43, (2008) 476-479.

Furetta C, Prokic M, Salamon R, Prokic, R. (2001a). Dosimetric characteristics of tissue equivalent thermoluminescent solid TL detectors based on lithium borate. *Nuclear Instruments Methods Phys Res A*, 456, 411－417.

Furetta, C. (2003). *Handbook of thermoluminescence*. World Scientific Publisher: New York.

Furetta, C. (2010). *Handbook of thermoluminescence*. (2nd edition). World scientific library: UK.

Furetta, C. Sanipoli and G. Kitis (2001b). Thermoluminescent kinetics of the perovskite KMgF3 activated by Ce and Er impurities. *Journal of Physics D: Applied Physics,* 34, 857–861.

Furetta, C., Prokic, M., Salamon, R., George Kitis. (2000). Dosimetric characterisation of a new production of MgB_4O_7:Dy,Na thermoluminescent material.

Applied Radiation and Isotopes. 52(2), 243-50.

Garlick, G.F.J., Gibson, A.F., (1948). The electron traps mechanism of luminescence in sulphide and silicate phosphors. *Proceedings of the Physical Society,* 60, 574–589.

Ghotbi, M., Ebrahim-Zadeh, M. (2004). Optical second harmonic generation properties of BiB3O6. *Opt. Express,*12(24), 6002–6019.

Gorelik, V.S.,Vdovin, A. V. and Moiseenko, V. N. (2003). Raman and Hyper-Rayleigh scattering in lithium tetraborate crystal. *Journal of Russian Laser Research,* 24, 553-605.

Gunduroa, T.K., Moharil, S.V. (2007). ESR study of phosphorus-related defects in irradiated LiF:Mg,Cu,P and related phosphors. *Radiation Measurement*, 42, 35–42.

Guoqing, Z., Jun, Z., Xingda, C., Heyu, Z., Siting, W., Ke, X., Peizhen, D. and Fuxi, G. (1998). *Journal of Crystal Growth*, 191, 517-519.

Harold,E. J. John, R. L. (1977). *The Physics of Radiology*. Fourth Edition, Charles C Thomas Springfield, Illinois, USA.

Haydar A. N. (2013). *Fundamental Properties of Cu-Doped and Co-doped SNO_2 of Lithium Potassium Borate Glass Exposed to Photon below 4 Gy*. Universiti Teknologi Malaysia: PhD Thesis.

Hoots, S. and Landrum, V. (1982). Glow-curve analysis for verification of dose in LiF chips. *Health Phys*, 43, 905–912.

Horowitz, Y., Delgado, A. Pradhan, A. S. and Yoder, R. C. (2002). *Radiation Protection Dosimetery*, 102, 269–277.

Hruby, A., Czech. J. (1972). Evaluation of glass-forming tendency by means of DTA. *Physica B.* 22, 1187-1191.

Hossain, I., Wagiran, H., Asn, H. (2012). *OPTOELECTRONİCS AND ADVANCED MATERİALS – RAPID COMMUNICATIONS*, 6(1-2), 162 – 164.

Hu, Z.U., Higashiyama, T., Yoshimura, M., Mori, Y. and Sasaki, T. (2000). Flux growth of the new nonlinear optical crystal: $K_2Al_2B_2O_7$. *Journal of Crystal Growth*, 212, 368-371.

Hubbell. J. H., Seltzer, S.M. (1982). Photon Mass Attenuation and energy absorption coefficients from 1 keV to 20 keV. *Int. J. Appl. Radiat. Isot.* 33, 1269 – 1290.

Hussin, R., Hamdan, S., Fazliana Abdul Halim D.N. and Shawal Husin, M. (2009). The origin of the emission in strontium magnesium pyrophosphate doped with Dy_2O_3. *Mater Chem Phys.*, 121, 37-41.

Huy, B.T., Quang, V.X., Ishii, M. (2010). Radioluminescent mechanism of $Li_2B_4O_7$:Cu crystal. Journal of Luminescence 130, 2142–2145.

ICRU (1976). Determination of absorbed dose in a patient irradiated by beams of x or gamma rays in radiotherapy procedures. ICRU report 24, Bethesda, Maryland.

ICRU (1998). Fundamental quantities and units for ionizing radiation. ICRU report 86, Bethesda, Maryland.

ICRU, Report No. 44, (1989). Tissue Substitutes in Radiation Dosimetry and Measurements, Bethesda, MD.

Ignatovych, M., Holovey, V., Watterich, A., Vidoczy, T. Baranyai, P., Kelemen, A., Chuiko, O. (2004). Luminescence characteristics of Cu- and Eu-doped Li2B4O7. Radiation Measurements 38, 567 – 570.

Ishii, M., Kuwano, Y., Asaba, S., Asai, T., Kawamura, M., Senguttuvan, N., Hayashi, T., Koboyashi, M., Nikl, M., Hosoya, S., Sakai, K., Adachi, T., Oku, T., Shimizu HM., (2004). Luminescence of doped lithium tetraborate single crystals and glass. *Radiation Measurements*, 38, 571-574.

Jackson, D. F., Hawkes D. J. (1981). X-ray attenuation coefficients of elements and mixtures. *Phys. Rev.* 70, 169-173.

Jayanchandran C.A, West M. and Shuttleworth E. (1968). In: Proceedings of the second conference on luminescence dosimetry, USA Atomic Energy Commission and Oak Ridge National Laboratory, 118–139.

Jaychandran, C.A. (1970). The response of thermoluminescent dosimetric lithium borates equivalent to air, water and soft tissue and of LiF TLD-100 to low energy X-Rays, *Physics in Medicine and Biology*, 15, 325-334.

Jiang, L.H., Zhang, Y.L., Li, C.Y., Pang, R., Hao, J.Q., Su, Q. (2008). Luminescence Characteristic of Borate Glasses and Electrical Properties. *Journal of Luminescence,* 128, 1898-1904.

Kamitsos, E.I., Karakassides, M.A., Chryssikos, G.D. (1987). Vibrational spectra of magnesium-sodium-borate glasses: 2. Raman and mid-infrared investigation of the network structure. *J. Phys. Chem.* 91 (5), 1073-1077.

Kauzmann, W. (1948). The nature of the glassy state and the behavior of liquids at low temperatures. *Chem. Rev.* 43, 219-224.

Kazanskaya, V.A., Kuzmin, V. V., Minaevaand, E. E., Minaevaand, E. E. and Sokolov, A. D. (1974). Proceedings of the Fourth International Conference on Luminescence Dosimetry, Krakow, Poland, Polish Academy of Sciences, 581.

Kenneth, W.W., Kenneth, G.D., and Raymond, D.E. (1988). *General Chemistry*, 3rd edn. Saunders College Publishing, Philadelphia.

Keszler, D.A., Tu, J.M. (1995). $CsLiB_6O_{10}$: a non-centrosymmetric polyborate. *Material Research Bulletin,* 30, 209-215.

Keszler, DA. (1996). High optical nonlinearities in aluminum borate crystals. The XVII Congress and General Assembly of the International Union of Crystallography, Seattle, W.A., August 8–16, paper EO501.

Khan, F.M. (1994). *The physics of Radiation therapy*. Second edition, Lippincott Williams & Wilkins, Philadelphia.

Kim, J.W., Yoon, C.S. and Gallagher, H.G. Dielectric properties of lithium triborate single crystals. (1997). *Applied Physics Letter*, 71, 3212-3214.

Knoll, G F. (2010). *Radiation Detection and Measurement*. (4th edition). Library of congress: USA.

Kitis, G., Furetta, C., Prokic, M., Prokic, V. (2000). Kinetic parameters of some tissue equivalent thermoluminescence materials. *J. Phys. D: Appl. Phys*. 33, 1252.

Kitis, G., Furetta, C., Sanipoli, C., (2002). Thermoluminescence properties of LiMgF3 doped with Ce, Er and Dy. Radiation protection dosimetry. 100(1-4), 247-50.

Kitis, G., Spiropulu, M., Papadopoulos, J., Charalambous, S. (1993). Heating rate e8ects on the TL glow peaks of three thermoluminescent phosphors. *Nucl. Instrum. Methods B* 73, 367–372.

Kortov, V. (2007). Materials for thermoluminescent dosimetry: current status and future trends. *Radiation Measurement,* 42, 576-581.

Kumar, P., Shukla, A.k., Yashonath, S. (2007). Relationship between ionic radius and pressure dependence of ionic conductivity in water. *Diffusion Fundamentals*, 6, 8.1-8.14.

Kutomi, Y., Kharita, M.H., Durrani, S.A. (1995). Characteristics of TL and PTTL glow curves of gamma irradiated pure $Li_2B_4O_7$ single crystals. *Radiat. Meas.* 24, 407-411.

Lacerda, S.R., Oliveira, J.M., Fermandes, M.H.V. (1997). TiO2-induced phase separation and crystallization in SiO2-3CaO.P2O5-MgO glass. *J Non-Cryst Solids.* 220, 197-205.

Lakshmanan, A.R., Bhuwan Chandra, R.C. (1982). Dosimetric Characteristic of $Li_2B_4O_7$:Cu, *Radiation Protection Dosimetery,* 2, 231-239.

Lakshminarayana, G. and Buddhudu. S. (2006).Spectral analysis of Sm3+ and Dy3+: B2O3–ZnO–PbO glasses. *Physica B*, 373, 100–106.

Lee, J.I., Kim, J.L., Chang, S.Y., Chung, K.S. and Choe, H.S.(2005). On the role of the dopants in LiF:Mg,Cu,Na,Si thermoluminescent material. *Radiation Protection Dosimetery,* 115, 340–344.

Lee, J.I., Kim, J.L., Pradhan, A.S., Kim, B.H., Chung, K.S., Choe, H.S. (2008). Role of dopants in LiF TLD materials. *Radiat Meas.* 43, 303-308.

Li, J., Hao, J.Q.,Li, C.Y., Zhang, C.X., Tang, Q., Zhang, Y.L., Su, Q., Wang, S.B. (2005). Thermally stimulated luminescence studies for dysprosium doped strontium tetraborate. *Radiation Measurements*, 39, 229-233.

Lide, D.R., (1990). *CRC Handbook of Chemistry and Physics*, 71st ed.; CRC Press: Boca Raton, FL, Ann Arbor, MI, Boston, MA, USA.

Lin, Y., Nan ,CW, Zhou, X., Wu, J., Wang H., Chen , D. and Xu, S. (2003). Preparation and characterization of long afterglow M2MgSi2O7-based (M: Ca, Sr, Ba) photoluminescent phosphors. *Material Chemistry Physics*, 82, 860-863.

Lines, E. (1991). Influence of d orbital on the non-linear optical response of transparent transition-metal oxides. *Journal of Physical Review B*, 43, 11978-11983.

Liu, L.Y., Zhang, H.L., Hao, J.Q., Li, C.Y., Tang, Q., Zhang, C.X. and Su, Q. (2005). Spectroscopic Properties of Inorganic and Organometallic Compounds. *Physics Status Solidi A*, 202, 2800-2805.

Liu, L.Y., Zhang, Y.L., Hao, J.Q., Li, C.Y., Tang, Q., Zhang, C.X. and Su, Q. (2006). Thermoluminescence studies of rare earth doped $Sr_2Mg(BO_3)_2$ phosphor. *Material Letter*, 60, 639-642.

Lushchik, C.H.B. (1956). The investigation of trapping centers in crystals by the method of thermal bleaching. *Soviet Physics*, 3, 390-399.

Madhukumar, K., Varma, H.K., Komath, M., Elias, T.S., Padmanbhan, V., Nair, C.M.K. (2007). Photoluminescence and thermoluminescence properties of tricalcium phosphate phosphors doped with dysprosium and europium. Material Sciences, 30(5), 527–534.

Mahesh, K., Weng, P.S. and Furetta, C. (1989). Thermoluminescence in solids and its application. Kent. *Nuclear Technology Publishing*, 10, 48-95.

Manam, J. and Sharm, A. S. K. (2004). Evaluation of trapping parameters of thermally stimulated luminescence glow curves in Cu-Doped Li2B4O7 phosphor. *Radiation Physics and Chemistry,* 72, 423-427.

Martini, M., Furetta, C., Sanipoli, C., Scacco, A., (1995). Somaiah, K. Spectrally resolved thermoluminescence of Cu and Eu doped $Li_2B_4O_7$. *Radiat. Eff. Def. Solids* 135, 133–136.

Maryam E.H., Elias, S., Nayereh, S., Wan Saffiey, W.A., Manizheh, N., Mansor, H. (2013). Thermoluminescence characteristics of copper activated calcium borate nanocrystals (CaB_4O_7:Cu). Journal of Luminescence. 141, 177–183.

McKeever, S. W. S. (1991). Measurements of Emission Spectra During Thermoluminescence (TL) from LiF:Mg,Cu,P. *Journal of Physics D: Applied Physics,* 24, 988–996.

McKeever, S.W.S and Moscovitch, M. (2003). On the advantages and disadvantages of optically stimulated luminescence dosimetry and thermoluminescence dosimetery. *Radiation Protection Dosimetery,* 104, 263-270.

Mckeever, S.W.S. (1985). *Thermoluminescence of solids.* Cambridge University Press. Cambridge.

McKeever, S.W.S. (2001). *Thermoluminescence of Solids.* Published by the press Syndicate of the University of Cambridge. Cambridge College State Science Series: USA.

McKeever, S.W.S., Moscovitch, M. and Townsend, P.D. (1995). *Thermoluminescence Dosimetry Materials: Properties and Uses,* Nuclear Technology Publishing: Kent.

McKinlay, A.F. (1981). *Thermoluminescence Dosimetry. Medical Physics Handbooks.* 5th edition. Adam Hilger Ltd, Bristol.

McParland, B. J. (2010). *Nuclear Medicine Radiation Dosimetry: Advanced Theoretical Principles.* Springer, united Kingdom.

Mohamed, S.N., Yahya, A.K., Maulude, M.F. (2011). Elastic And Structural Properties Of Teoz - Nb2os -Zno Glasses. PhD. Thesis. Universiti Teknologi Mara, Malaysia.

Moryc, U. and Ptak, W.S. (1999), Infrared spectra of β-BaB2O4 and LiB3O5: new nonlinear optical materials. *Journal of Molecular Structure*, 511-512, 241-249.

Moyer, R.F., McElroy, W.R., O'Brien, J.E. and Chamberlain, C.C. (1983). A surface bolus material for high-energy photon and electron therapy. *Journal of Radiology*, 146, 531-532.

Nageswara Rao, P., Laxmi Kanth, C., Krishna Rao, D., Veeraiah, N. (2005). Influence of titanium ions on optical properties of AF–PbO–B2O3 glasses. *Journal of Quantitative Spectroscopy & Radiative Transfer*. 95, 373–386.

Nakajima,T., Murayama, Y., Matsuzawa, T. and Koyano, A. (1978). Development of a New Highly Sensitive LiF Thermoluminescence Dosimeter and Its Applications. *Nuclear Instruments and Methods*, 157, 155-162.

Norbert, K. (1990). Recent applications of glass science. *Journal Non-Cryst Solids*, 123, 377-384.

Oberhoffer, M. and Schermann, A. (1981). *Applied thermoluminescence dosimetery*. Adam Hilger Ltd: Bristol.

Özdemir, Z. Ozbayoglu, V., Yilmaz, A. (2007). Investigation of thermoluminescence properties of metal oxide doped lithium triborate. *J Mater Science*. 42, 8501–8508.

Oztas, M. (2006). Characteristics of annealed ZnO:Cu nanoparticles prepared by spray pyrolysis. *Journal of Materials Science: Materials in Electronic*s 17(11), 937-941.

Padlyak, B., Ryba-Romanowski,W., Lisiechi, R., Adamiv, V., Burak, Y., Teslyuk.I. (2010b). Optical Spectra and Luminescence Kinetics of the Sm^{3+} and Yb^{3+} centres in the Lithium Tetraborate Glasses. *Optica Applicata*, XL(2), 427-438.

Padlyak, B.V., Ryba-Romanowski, W., Lisiecki, R., Smyrnov. O., Drzewiecki, A., Burak, Y., Adamiv, V., Teslyuk, I. (2010a). *Journal of Non-Crystalline Solids*, 356, 2033–2037.

Padlyak, B.V., Wojtowicz, W., Adamiv, V.T., Burak, Y.V., Teslyuk, I.M. (2009) in: Y. Zhydachevskii, Book of Abstracts,—Fabrication, Properties and Application, Ed., (OMEE-2009)". Lviv, Ukraine, Lviv Polytechnic National University, 90.

Pagonis, V., Kitis, G. and Furetta, C. (2006). *Numerical and practical exercises in thermoluminescence*. Springer: USA.

Park, K. S. Ahna, J. K., Kima, D. J., Kima, H. K. and Wanga, H. Y. H. (2002). Growth and properties of Li2B4O7 single crystals. *Journal of Crystal Growth.* 249, 483-486.

Park, K.S., Ahn, J.K., Kim, D.J., Kim, H.K., Hwang, Y.H., Kim, D.S., Park, M.H., Park, Y., Yoon, J.J., Leem, J.Y. (2003). *Journal of Crystal Growth*, 249, 483-486.

Parthasaradhi, K. (1968). Studies on the effective atomic numbers in the alloys for gamma ray interactions in the energy region 100 – 662 KeV. *Indian J. Pure. Appl. Phys.,* 6, 609-614.

Patil R.R. and Moharil, S. V. (1995). Photoluminescence of Cu^{+2} in Alkali Halides. *Journal of Luminescence,* 63, 339–344.

Patil, R.R., Moharil, S.V., Dhopte, S.M., Muthal, P.L., Kondawar, V.K. (2003).Thermoluminescence in some copper-doped compounds. *Physica Status Solidi (a).* 199(3), 527-532.

Paul, A. (1975). Optical and esr spectra of titanium (III) in Na2O-B2O3 and Na2O-P_2O_5 glasses. *Journal of Material Science,* 10, 692-696.

Pekpak, E, Yılmaz, A. and Özbayoglu, G. (2010). An Overview on Preparation and TL Characterization of Lithium Borates for Dosimetric Use. *The Open Mineral Processing Journal,3,* 14-24.

Pekpak, E., Gülhan, O., Aysen, Y., (2009). Thermoluminescent Characteristics of Lithium Tetraborate. IV International Boron Symposium, 15-17/October, 2009 Eskişehir-TURKEY, ISBN: 978-9944-89-790-7.

Peng, W.Q., Cong, G.W., Qu, S.C., Wang,Z.G. (2006). Synthesis and photoluminescence of ZnS:Cu nanoparticles. Optical Materials 29, 313–317.

Piters, T.M., Bos, A.J.J. (1993). A model for the influence of defect interactions during heating on thermoluminescence in LiF:Mg,Ti (TLD-100). *J. Phys. D: Appl. Phys.* 26, 2255-2260.

Podgorsak, E.B. (2005). Radiation oncology physics: *A handbook for teacher and students.* Vienna : International Atomic Energy Agency.

Pontuschka, W.M., Kanashiro, L.S., Courrol, L.C. (2001). Luminescence mechanisms for borate glasses: the role of local structural units. *Glass Physics and Chemistry,* 27, 37–47.

Portal, G. (1981). *Preparation and properties of principal TL products, In: Applied thermoluminescence dosimetry,* Oberhoffer, M. and Schermann, A. Bristol : Adam Hilger Ltd., 97-122.

Pradhan, A. S. (1981). Thermoluminescence dosimetery and its applications. *Radiation Protection Dosimetery,* 1, 153-167.

Prokic, M. (2001). Lithium borate solid TL detectors. *Radiation Measurement,* 33, 393—396.

Prokie M. (2002). Dosimeteric Charetceristics of Li2B4O7:Cu,Ag,P Solid TL Detectors. *Radiation Protection Dosimetery*, 100, 265–268.

Puppalwar, S.P., Dhoble, S.J. (2013). Development of high sensitive LiNaSO4:Cu,Mg phosphor for TL dosimetry. *Journal of Luminescence***, 137**, 245-251.

Puppalwar, S.P., Dhoble, S.J., Dhoble, N.S., Animesh K., (2012). Luminescence characteristics of Li2NaBF6: Cu phosphor. *Nuclear Instrument and Methods B,* 74, 167-171.

Ramadevudu, G., Laxmisrinivasa, S., Shareefuddin, M.D., Narasimha, M. (2011). FTIR and some physical properties of alkaline earth borate glasses containing heavy metals oxides. *IJEST* 3 (9), 6998-7005.

Randall, J.T., Wilkins, M.H.F. (1945). Phosphorescence and electron traps. *Proceedings of the Royal Society of London,* A184, 366-407.

Rao, R.B., Veeraiah, N. (2004). Study on some physical properties of Li_2O–MO–B_2O_3: V_2O_5 glasses. *Physica B.* 348, 256-259.

Rawat, N. S., Kulkarni, M. S., Mishra, D. R., Bhatt, B. C., Sunta, C. M., Gupta, S. K. and Sharma, D. N. (2009). Use of initial rise method o analyze a general order kinetic thermoluminescence glow curve. *NIM B,* 207, 3475-3479.

Reddy, R.R., Nazeer Ahammed, Y., Abdul Azeem, P., Rama Gopal, K., Rao, T.V.R., Buddhudu, S., Sooraj Hussain, N. (2003). *J. Quant. Spectrosc.* 77, 149-153.

Rey, L. (2003). Thermoluminescence ofultra-high dilutions of lithium chloride and sodium chloride. *Physica A,* 323, 67 – 74.

Rivera, T. (2011). *Advances in ceramics-synthesis and characterization, processing and Specific Applications. in; C.* Sikalidis (Ed.), InTech-Publisher, Croatia, 127.

Rojas,S.S., Yukimitu, K., de Camargo, A.S.S., Nunes, L.A.O., Hernandes, A.C. (2006). Undoped and calcium doped borate glass system for thermoluminescent dosimeter. *Journal of Non-Crystalline Solids,* 352, 3608-3612.

Rzyski B, Nambi KSV. (1977). In: Proc. 5th Int. Conf. on luminescence dosimetry, Sao Paulo, Brazil.

Salah, N., Sahare, P.D., Rupasoy, A.A. (2007). Thermoluminescence of nanocrystalline LiF:Mg, Cu, P. J. Lumin., 124, 357-364.

Sangeeta and Sabharwal, S.C. (2004). Kinetics of thermally stimulated luminescence from alkaline earth borates. *Journal of Luminescence*, 109, 69-74.

Santiago, M., Lester, M., Caselli, E., Lavat A, Ges A., Spano F., Kessler C. (1998). Thermoluminescence of Sodium Borate Compounds Containing Copper. *Journal of Material Science Letter*, 17, 1293-1296.

Sasaki, T., Mori, Y., Yoshimura, M., Yap, Y.K., Kamimura, T. (2000). *Material Science Engineer R*, 30(1-2), 1-54.

Schön and Klasens, H.A. (1946). Transfer of energy between centers in zinc sulphide phosphors. *Nature*, 158, 306-308.

Schulman, J.H., Kirk, R.D., West, E.J. (1965). Use of lithium borate for thermoluminescence dosimetry. USAEC Symposium series 650637, Luminescence Dosimetery, 113-118.

Schweizer, S., Spaeth, J.M and Bastow, T.J. (1998). Generation of F centres and hole centres in the nonstoichiometric X-ray storage phosphor BaFBr. *Journal of Physics: Condensed Material*, **10,** 9111.

Senguttuvan, N., Ishii, M., Shimoyama, M., Kobayashi, M., Tsutsui, N., Nikl, M., Dusek, M., Shimizu, HM., Oku, T., Adachi, T., Sakai, K. (2002). *Journal of Nuclear Instrument and Methods Physical Research A*, 486, 264-267.

Shaim, A., Et–tabirou, M. (2003). Role of titanium in sodium titanophosphate glasses and a model of structural units. *Journal of Material Chemistry and Physics,* 80, 63-67.

Shapiro, J. (2002). *Radiation protection: a guide for scientists, regulators, and physicians*. Library of congress-USA.

Shimoji, N., Hashimoto, T., Nasu, H., Kamiya, K.L. (2003). Non-linear optical properties of $Li_2O–TiO_2–P_2O_5$ glasses. *Journal of Non-Crystal Solids,* 50 (2003) 324.

Shoushan, W., (1988). The dependence of thermoluminescence response and glow curve structure of LiF(Mg,Cu,P) TL materials on Mg,Cu,P dopants concentration, *Radiation Protection Dosimetery,* 25, 133–136.

Singh., L., Chopra, V., Lochab, S.P. (2011). Synthesis and characterization of thermoluminescent Li2B4O7 nanophosphor. *Journal of Luminescence.* 131, 1177–1183.

Soramasu, N. and Yasuno, Y. (1996). Perfectly Tissue Equivalent TLD Phosphor Li2B4O7:Cu,Pb. In: Proc. 9th International Congress IRPA International Congress on Radiation Protection, IRPA 9, Vienna, Austria, April 1996. 4, 312–314.

Spurný, Z., Novotný, J. (1965). *Journal of Physics and Chemistry of Solids*. 26(7), 1107-1110.

Srivastava, J. K. and Supe, S. J. (1989). The Thermoluminescence Characteristation of $Li_2B_4O_7$ Doped with Cu. J. *Phys. D. Appl.Phys*. 22, 1537–1543.

Syam, P., Srinivasa Reddy. M., Ravi Kumar, V., Veeraiah, N. (2007). Spectroscopic and dielectric studies on $PbO–MoO_3–B_2O_3$ glasses incorporating small concentrations of TiO_2. *Philosophical Magazine.* 87(36), 5763-5787.

Takenaga, M., Yamamoto, O. and Yamashita, T. Preparation and Characteristics of $Li_2B_4O_7$:Cu Phosphor. *Nucl. Instrum.Methods*. 175, 77–78 (1980).

Takenaga, M., Yamamoto, O., Yamashita, T. A new phosphor $Li_2B_4O_7$: Cu for TLD. *Health Phys.* 44, (1983) 387–393.

Taylor G. C. and Lilley, E. (1982). *II Journal of Physics D*: *Applied Physics*, 15, 1253–1263.

Thompson, JJ, Ziemer PL. (1973). The thermoluminescent properties of lithium borate activated by silver. *Health Physics*, 25, 435-438.

Tochilin, E., and Goldstein, N. (1966). Dose rate at spectral measurements from pulsed X –ray generator. *Health Physics.* 12, 1705-1711.

Uhlamn, D.R, and Kreidl, N.J. (1983). *Glass Science and Technology*. (l.1 edition). Academic Press: New York.

Van der Marel, H.W. (1959). *Potassium Fixation, a beneficial Soil Charecteristic for Crop Production,* Pflamzenernahr, Dung, Bodenk. 84, 51-62.

Venkateswara Rao,G., Reddy,P.Y., Veeraiah, N. (2002).Thermoluminescence studies on Li2O–CaF2–B2O3 glasses doped with manganese ions. *Material Letter,* 57, 403–408.

Wall, B.F., Driscoll, C.M., Strong, J.C., Fisher, E.S. (1982). The suitability of different preparations of thermoluminescent lithium borate for medical dosimetry. *Physics in Medicine and Biology,* 27, 1023-1034.

Wua, L., Chena, X.L., Tua, Q.Y., Hea, M., Zhanga, Y. and Xua, Y.P. (2002). *Journal of Alloy Compound,* 333, 150-154.

Xiong, Z.,Ding, P., Tang, Q., Chen, J., Shi, W. (2011). Thermoluminescence Spectra of Lithium Tetraborate Single Crystal. *Advanced Materials Research.* 160(162), 252-255.

Xiong, ZY., Tang, Q. and Zhang CX. (2007). *Science in China Series G: Physics, Mechanics and Astronomy.* 50(3), 311-320.

Yang, B., Townsend, P.D., Rowlands, A.P. (1998). Low temperature thermoluminescence of rare earth doped lanthanum fluoride. *Physical Review B,* 57, 178–188.

Yukihara, E. G., Gaza, R.,. McKeever, S. W. S., and Soares, C. G. (2004). *Radiation Measurement,* 38, 59-70.

Yusoff, A.L. (2005). *Development of silica-based thermoluminescence dosimeters*. University of Exeter: PhD Thesis.

Zadneprowski, B.I., Eremin, N.E., Paskhalov, A.A., (2005). Luminescence and optical properties of sheelite tungstate Ukraine. *Functional Materials*, 12, 261-267.

Zheng Zheng, Chen Jiansheng, Zhu Jiating, Dai Honggui, Zhao Youghu, Hu Shangze, and Fang Jie. (1997). *Radiat. Phys. Chem.* 50(3), 303 – 305.

Zhu, X., Li, Q. (1997). Origin of optical nonlinearity for PbO, TiO2, K2O, and SiO2 optical glasses. *Appl. Phys. Lett.* 71, 867-870.