DEVELOPMENT AND CHARACTERIZATION OF AN ACOUSTO-OPTIC MODULATOR

NAZARIAH BINTI MAT DAUD

UNIVERSITI TEKNOLOGI MALAYSIA

DEVELOPMENT AND CHARACTERIZATION OF AN ACOUSTO-OPTIC MODULATOR

NAZARIAH BINTI MAT DAUD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Science (Physics)

Faculty of Science
Universiti Teknologi Malaysia

SEPTEMBER 2008

To my beloved mum

Meriam Mat Hassan

My adorable brothers and sisters

Mizarman, Nurhidayati, Nurul Hawani, Ahmad Akbaruddin,

Nur Suhada, Nor Izati and Nazatul Wahida

Thank you for all your patience and support to realize my dream

I love all of you so much

To my late beloved father

Mat Daud bin Deraman

I have completed your dream

Love and miss you always

ACKNOWLEDGEMENT

In the name of Allah, Most Gracious, Most Merciful. Praise be to Allah, the Cherisher and Sustainer of the worlds. For His Mercy has given me the strength and time to complete this project.

I would like to express my appreciation to my respected supervisor, Associate Professor Dr. Mohd Khairi Saidin, Professor Dr. Noriah Bidin and Dr. Yaacob Mat Daud for their supervision, guidance, enjoyable discussion and motivation throughout this study.

Beside them, I have much pleasure to those who have assisted me in various ways in carrying out the experimental works. They are my late technician Mr. Mohammed Nyan Abu Bakar, my new technician Mr. Abd. Rasid Isnin, Mr. Subre Husin, and Mr. Mohd Nazri Kamaruddin. My thanks are also due to Government of Malaysia through IRPA grant vote 74533 for giving us financial support.

Last but not least, my appreciations go to my family for continuing support, patience throughout the present work and who have favored me with correspondence, I have much pleasure in expressing my obligation. May Allah bless those who have involved in this project.

ABSTRACT

An acousto-optic modulator (AOM) has been developed and characterized. The system was evaluated by feeding radio frequency (RF) signal on the AOM crystal (fused silica crystal) to generate acoustic wave. The AOM then was illuminated by He-Ne laser at its Bragg angle and the modulated beam was characterized by using a beam profiler, a power meter, and an oscilloscope. The observation result showed that the modulated beam was diffracted into zero and first order. The Bragg angle linearly increases in the range of 0.127° to 0.256° as the RF signal increase from 30 MHz to 65 MHz. The diffraction efficiency per RF drive power was found to be maximum at 50 MHz. The output power for the zero order diffraction was decreased, while the first order diffraction was increased with the increases in the RF drive power. The average power transmittance coefficient of the AOM for modulated beam is about 72.8 % and the power loss is about 0.1dB/cm at 50 MHz RF signal input. The modulated beam signal was obtained in periodical waveform having pulse width of 48.5 μs, with amplitude of 5.32 V and rise time of 18.7 μs. The pulse width and the amplitude of the modulated signal was found to increase with increases in the input RF pulses width and RF drive power, respectively.

ABSTRAK

Pemodulasi akusto-optik (AOM) telah dibangun dan dicirikan. Sistem ini dinilai dengan menyuapkan isyarat frekuensi radio (RF) kepada hablur AOM (hablur silika lakur) bagi menjana gelombang akustik. AOM tersebut kemudian disinari dengan He-Ne laser pada sudut Bragg dan alur yang termodulasi telah dicirikan menggunakan profil alur, meter kuasa dan osiloskop. Hasil pemerhatian menunjukkan alur yang termodulasi telah dibelaukan kepada tertib sifar dan pertama. Sudut Bragg didapati meningkat secara linear dalam julat 0.127° hingga 0.256° apabila isyarat RF meningkat dari 30 MHz kepada 65 MHz. Kecekapan pembelauan per kuasa pemacu RF yang maksimum diperolehi pada 50 MHz. Kuasa keluaran pembelauan tertib sifar menurun dan manakala pada pembelauan tertib pertama didapati meningkat dengan peningkatan kuasa pemacu RF. AOM mempamerkan purata pekali kehantaran 72.8% ke atas kuasa alur termodulasi dan kehilangan kuasa sebanyak 0.1dB/cm pada 50 MHz isyarat RF masukan. Isyarat alur yang termodulasi diperolehi dalam bentuk gelombang berkala dengan lebar denyut pada 48.5 μs, amplitud pada 5.32 V dan tempoh naik pada 18.7 μs. Lebar denyut dan amplitud alur yang termodulasi ini didapati meningkat masing-masing dengan pertambahan lebar denyut RF masukan dan kuasa pemacu RF.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating current
AO	-	Acousto-optic
AOM	-	Acousto-optic modulator
CW	-	Continuous wave
DC	-	Direct current
EMI	-	Electromagnetic interferences
FWHM	-	Full wave half maximum
IC	-	Integrated circuit
LED	-	Light emitting diode
MCLR	-	Master clear
OSC	-	Oscillator
PIC	-	Programmable integrated circuit
RFI	-	Radio frequency interferences
RF	-	Radio frequency
VAC	-	Alternating current voltage
VDC	-	Direct current voltage

LIST OF SYMBOLS

A_c	-	Amplitude of carrier wave
b	-	A constant depending on the experimental setup
B	-	Amplitude of modulating wave
c	-	Light velocity
d	-	Spacing between layers
D_{in}	-	Incident laser beam diameter
f	-	Frequency of acoustic waves
h	-	Height of AO material
H	-	Height of interaction region
I_0	-	Incident optical beam intensity
I_1	-	First order diffraction intensity
k_a	-	Wave vector of phonon
K	-	Wave vector of photon
K'	-	Wave vector of new photon
L	-	Length of interaction region
m	-	Diffraction order
M	-	Figure of merit
n	-	Refractive index
p	-	Strain optic coefficient
P_0	-	Zero order beam power

P_1	-	First order beam power
P_a	-	Acoustic power
P_{in}	-	He-Ne power before passing through AO material
P_T	-	He-Ne power after passing through AO material
Q	-	Quality factor
S	-	Acoustic strain
t	-	Temporal response
t_r	-	Rise time
T	-	Pulse duration of pulse generator
V	-	Velocity of sound in material
V_s	-	Input voltage
x	-	Distance between zero to first order diffraction
X	-	Thickness of AO material
y	-	Distance between AOM to beam profiler
β	-	A constant associated with laser beam profile
α	-	Attenuation coefficient
ρ	-	Density of material
η	-	Diffraction efficiency
ν	-	Grating strength
$\hbar$	-	Planck constant
Λ	-	Wavelength of the acoustic waves
ω_a	-	Angular frequency of phonon
ω_c	-	Angular frequency of carrier wave
ω_l	-	Angular frequency of photon
ω_o	-	Angular frequency of new phonon

θ_B	-	Bragg angle
θ_d	-	Diffracted angle
θ_i	-	Incident angle
φ_c	-	Phase of carrier wave
θ_m	-	Raman-Nath angle
^oC	-	Temperature (Celcius)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, rapid new developments have been made in optical technology. Developments were made in infrared LED inside TV remotes, miniature semiconductors laser systems inside CD players, laser bar code scanners at supermarkets and complex optical fiber networks that transmit information. The use of lasers and optics are also wide spread in fields such as medicine, satellite communication, and manufacturing. Many signal processing applications require the ability to analyze enormous amounts of information at very high speeds. Optical information processing techniques are capable of satisfying these requirements. One particular technique that is capable of meeting this demand is the diffraction of light by acousto-optic (AO) interaction (Dunn, 1998).

At the present time, AO methods of light beam regulation find wide applications in many areas of science and technology. Numerous investigations have proved high efficiency of AO regulations of amplitude, frequency, phase and polarization of optical waves. Due to high speed of operations, reliability and simplicity of design, AO devices such as modulator, deflectors and filters have become common instruments in every laboratory (Balakshy and Kostyuk, 2005).

Common uses of AO devices are for modulating light for communication, deflecting light, convolving or correlating signals, optical matrix processing, analyzing the spectrum of signals, optical sources, laser mode lockers, Q-switchers, delay lines, image processing, general and adaptive signal processing, tomographic transformations, optical switches, neural networks, optical computing, and much more. The applications of acousto-optics are extremely rich as is the theory (Pollack, 2002).

One of the most common applications of AO devices is the acousto-optic modulator. The acousto-optic modulator (AOM) is a fascinating physical device. It can be easily used in experiments demonstrating principles fundamental to the fields of communications, signal processing and optical information processing. The AOM consists of small block of crystal or glass, commonly called as AO material to which a piezoelectric transducer is bonded. When a radio frequency (RF) signal is applied to the transducer, a travelling acoustic wave is generated within the acoustic medium. In this state, the AOM can be used to deflect, diffract, modulate, or otherwise manipulate a coherent light beam such as that supplied by a laser (Gies and Poon, 2002).

Overall, this project is to develop and characterize AOM that can modulate CW laser into pulse laser. It consists of three parts; circuits design development, optical alignment and finally the characterization of AOM .Hopefully, the AOM can be used as a part of internal or external laser cavity of the mode-locking laser.

1.2 Research Background

The development of the laser in 1960 stimulated the demand for method to switch, modulate, and deflect light for the great variety of applications that were foreseen. The principal mechanism then proposed for producing fast, high resolution deflection of laser light involved AO interaction (Gottlieb *et al*., 1983).

The interaction between sound and light is usually termed AO interaction (Banerjee and Poon, 1991). All AO interactions are based on the photo-elastic effect (Goutzoulis and Kludzin, 1994). The compression and rarefraction of the medium is known as photoelastic effect. The photoelastic effect changes the refractive index of the medium (Dunn, 1998). There are two important regimes for AO interaction: the Raman-Nath diffraction regime, also known as the Debye-Sears effect, and the Bragg diffraction regime. The diffraction occurs depending on the angle of incidence of the beam to be diffracted. In Bragg diffraction, the laser beam may diffract into only one diffracted order and many distinct diffracted orders obtained from Raman-Nath diffraction (Quate *et al*., 1965; Young *et al*., 1981; Csele, 2004).

The AO effect describes the interaction of optical waves with acoustic waves in a material medium (Filkins, 2003). Acoustic waves were studied extensively in the past century. In the year 1885, surface acoustic waves were first described by Lord Rayleigh as pertained to earth quakes (Pollack, 2000). The diffraction of light by acoustic waves in liquids and solids was first predicted by Brillouin in 1922. Experimental verification of the AO effect did not occur until 1932 when two independent groups, Debye and Sears in U.S, and Lucas and Biquard in France published their results (Young *et al*., 1981; Korpel, 1981; Filkins, 2003). The AO effect can be used to control the frequency, intensity and direction of an optical beam. The ability to modulate the light waves by electrical signal through AO effect provides a powerful means for optically processing information. The AO effect was primarily a subject of academic interest until the invention of laser in 1960. The need then arose for modulation and deflection of laser beams. Light modulating and deflecting devices based on AO effect were developed and AO technology was born.

Research and development over the last several decades have produced many types of AO devices including AOM, acousto-optic tunable filters (AOTF), acousto-optic deflectors (AOD), correlators/convolvers and spectrum analyzers (Filkins, 2003). One of the common use AO devices is AOM. Some of the earliest efforts at fabricating AOM were initiated 50 years ago, long before the invention of the laser. One of the earliest uses of an AOM in an electro optic system was for large screen projection of television images in theatres, developed in the late 1930 by the Scophony Laboratory London (Goutzoulis and Pape, 1994).

By 1967 several important results on AO devices had been reported. These include the works of Korpel *et al*. (1981) on acoustic beam steering and by Dixon (1967) on AO interaction in anisotropic media. Gordon (1966) wrote a general review on deflection and modulation devices. Maydan (1970) have discuss and demonstrate the use of ultrasonic wave to pulse modulate light of He-Ne laser by using AOM and 12 ns pulse duration obtained from the works . The works of McNeill *et al*. (1994) shows how an AOM operating in the first Bragg regime together with additional electronics can produce pulse-width modulated signals. Since then, there has been a rapid progress of AO devices, primarily due to the development of superior AO materials and efficient broadband transducers. Various AO devices have evolved with many applications in diverse fields (Chang, 1976).

The used of an AOM inside a laser cavity has been another major application area. This is because the AO effect occurs in crystals of all classes and amorphous solids, and AO material with excellent optical qualities are easy to found. These intracavity applications include Q-Switching, mode locking and cavity dumping. AOM has been applied in the mode locking technique for many years (Myslinski, 1986). Darrow and Jain (1991) have reported the mode locking of solid state laser by inserting an AOM in the laser cavity. New development was made by Jabczyński *et al*. (2006) by operating the AOM in playing the double role of Q-Switch and mode locker in a diode pumped Nd: YVO_4 laser. Today, laser-diode end pumped Nd:YLF or Nd:YAG lasers that are actively mode locked with an AOM provide output pulses with pulse widths on the order of 10-20 picoseconds (Koechner, 2006). AOM can also be used outside the laser cavity for mode locking, which has been useful in optical heterodyne applications. Such research of external cavity mode locking was demonstrated by Dienes (1973) by inserting the AOM outside the laser cavity of CW dye lasers.

The most common means for generating the required ultrasonic beam is by electrically driving a piezoelectric transducer which is bonded to a suitable acousto-optic material (Pinnow, 1970). The choice of material for AO devices depends on its optical transmission in the wavelength range required, the availability of large crystals, acoustic absorption and particularly its AO efficiency (Sruby and Drain, 1990). Selected list of the most useful acousto-optic material were given by Pinnow

(1970) and Chang (1976), where the figure of merit, acoustic loss and range of optical transmission are listed. The widely used AO materials are such as fused silica, lithium niobate ($LiNbO_3$), lead molybdate, ($PbMoO_4$), tellurium dioxide (TeO_2) and dense flint glass. Although the figure of merit of fused silica is quite low, its optical high quality, low optical absorption and high damage threshold make it superior to other (Koechner, 2006). In nearly AO Q-Switches used today, fused silica is employed primarily because of its excellent optical quality and high threshold for optical damage. For mode locker applications, fused silica is generally used for the visible and Ge for 10.6 μm (Chang, 1976).

The acoustic wave is launched into the AO material by a piezoelectric transducer. Recently, a variety of new piezoelectric transducer materials has been available. The most commonly used piezoelectric transducers are single crystals Lithium Niobate plate transducer and ZnO thin film transducers (Young *et al*., 1981). Among these materials, $LiNbO_3$ is probably the most widely used in practice. The essential properties of $LiNbO_3$ are summarized by Chang (1976). The transducer was driven by electronic signal in order to produce sound energy. The electronic consist of an RF carrier frequency oscillator, a balanced diode RF mixer for impressing an electronic video signal onto the carrier and a wide band power amplifier to drive the AOM at peak diffraction efficiency (Johnson, 1994). The electrical signals that drive AOM must generally be bandpass in nature, with frequency content typically in the range of 1 MHz to 1 GHz. Reasonably large fractional bandwidth are acceptable, depending on the nature of the AO material and the transducer (Rhodes, 1981).

In this present works, we will focus on the development and characterization of AOM. Fused silica has been chosen as the AO material. The detail of this whole project will be discussed later.

1.3 Problem Statement

A number of applications, such as laser machining, medical and dental surgery processes, and certain scientific research experiments require a laser which emits short discrete pulses of very high peak power rather than a CW laser. AOM is a vital device for producing short pulse and high peak power laser. To apply such AOM system into the laser system, requires knowledge and experience. Hence this research was carried out to achieve such goal and get a better understanding about the fundamental principle of AOM. To make sure the AOM can performed at optimum level for modulating laser beam, we need to develop its driver, temperature stabilizer and characterize the AOM output.

1.4 Research Objective

The objectives of this project are to develop and characterized an acousto-optic modulator. This involves:

1) Designing the acousto-optic modulator driver
2) Developing a temperature stabilizer
3) Aligning the acousto-optic modulator system
4) Characterizing of the modulation beam

1.5 Research Scope

In this research, AOM was employed as the active element in the system. Fused silica was employed as the AO material. Piezoelectric transducer was coupled with AOM driver to induce acoustic wave. He-Ne laser with 632.8 nm was used as a light source. AOM driving circuit comprised of pulse generator and signal mixer were developed. A temperature controller was constructed to stabilize the AO material. The AOM was precisely aligned with rotating stage in order to diffract the light at Bragg angle. The characterization of AOM was carried out in term of laser beam profile, power and signal configuration. The RF signal was conducted in the range of 30 MHz to 65 MHz. RF drive power was manipulated within 1.00 W to 4.00 W. Input RF pulses was regulated in between 50 μs to 100 μs.

1.6 Thesis Outline

This thesis composes of six chapters. The first chapter of this thesis is reviewing an introduction and overview of the previous research regarding the AOM. The objective and scope for this research is also address briefly to clarify the aim of this research.

Chapter 2 presents the theoretical background related to this research. It explains the principle of acousto-optic interaction. The Bragg diffraction also enlighten in detail as it is important in characterization of beam modulation.

Chapter 3 recovers how the methodology of this research is conducted. The technique of AOM driver development is described, which comprise several main circuits. It is also explains the method for characterization of modulation output. This includes the procedure of experimental setup for Bragg angle alignment, laser beam profile, power and signal measurement.

The design and development process of the AOM driving circuit is revealed in Chapter 4. This covers all the circuits including the temperature controller, pulse generator, signal mixer and power supplies. The details of the circuit together with circuit diagrams of electronics components type, serial number, circuit operation and output, are also discussed.

Chapter 5 discussed the characterization of AOM output in term of beam profile, power and signal. Details analysis of beam profile that covers diffraction angle, diffraction efficiency and optimum frequency is carried out. Measurement of beam power will lead to discover the power of modulated beam and optical losses. The modulated signal pulse width, rise time and amplitude are also presented.

Finally the conclusion of the project is described in Chapter 6. This includes the summarization of the whole project. Some works to be carried out in the future are suggested.

REFERENCES

Analog Devices, Inc. (1994). *250 MHz, Voltage Output 4-Quadrant Multiplier AD835*. U.S.A: Datasheet.

Aronhime, P. (2005a). *Operational Amplifiers*. In Whitaker, J.C. (Ed.). *The Electronics Handbook*. (2nd ed.) (pp. 611-640). U.S.A: Taylor & Francis Group.

Aronhime, P. (2005b). *Applications of Operational Amplifiers*. In Whitaker, J.C. (Ed.). *The Electronics Handbook* (2nd ed.) (pp. 641-676). U.S.A: Taylor & Francis Group.

Beach,D., Shotwell, A., and Essue, P. (1993). *Applications of Lasers and Laser System*. New Jersey: Prentice Hall.

Banerjee, P.P., and Poon T.C. (1991). *Principle of Applied Optics*. U.S.A: Irwin.

Balakshy, V.I., and Kostyuk, D.E. (2005). Measurement of Optic Signals Phase Structure by Means of Bragg Acousto-Optic Interaction. *CAOL*, 234-238.

Black, H.S. (1953). *Modulation Theory*. New York: D.Van Nostrand Company, Inc.

Chang, I.C. (1976). Acoustooptic Devices and Applications. *IEEE Transactions on Sonics and Ultrasonics*. 23(1), 2-22.

Chang, I.C. (1995). *Acousto-Optic Devices and Applications*. In Bass, M. (Ed.) *Handbook of Optics: Devices, Measurement, and Properties*. (2nd ed) (pp. 12.1-12.54). U.S.A: McGraw-Hill, Inc.

Chow, K.K. and Leonard, W.B. (1970). Efficient Octave-Bandwidth Microwave Light Modulators. IEEE *Journal of Quantum Electronics*. 6(12), 789-793.

Csele, M. (2004). *Fundamentals of Light Sources and Lasers*. New Jersey: John Wiley & Sons, Inc.

Darrow, J.T. and Jain, R.K. (1991). Active Modelocking of Broad Band Continuous Wave Lasers. *IEEE Journal of Quantum Electronics*. 27(4), 1048-1060.

Dias, J.F, (1999). *Transducers*. In Coombs, C.F. Jr. (Ed.). *Electronic Instrument Handbook*. (3rd ed.) (pp. 5.1-5.56). U.S.A: McGraw-Hill, Inc.

Dickey, F.M., and Holswade, S.C. (2000). *Laser Beam Shaping: Theory and Techniques*. New York: Marcel Dekker, Inc.

Dienes, A. (1974). Mode-Locked CW Dye Lasers. *Opto-electronics*. 6, 99-113.

Dixon, R.W. (1967). Acoustic diffraction of Light in Anisotropic Media. IEEE *Journal of Quantum Electronics*.3(2), 85-93.

Dunn, D.B. (1998). *Real Time Image Processing by Using Acousto-Optic Bragg Diffraction*. Doctor Philosophy, Virginia Polytechnic Institute and State University, Virginia.

Filkins, R.J. (2003). *Experimental Investigation of the All-Optical Acousto-Optic Effect for Device Applications*. Doctor Philosophy, Rensselaer Polytechnic Institute, Troy.

Floyd, T.L. (1999). *Electronic Devices*. (5th ed.) New Jersey: Prentice Hall, Inc.

Gallo, J.S. (1999). *Power Supplies*. In Coombs, C.F. Jr. (Ed.). *Electronic Instrument Handbook*. (3rd ed.) (pp. 11.1-11.26). U.S.A: McGraw-Hill.

Gies. D.T., and Poon, T. (2002). Measurement of Acoustic Radiation in an Acousto-Optic Modulator. *Proceedings IEEE Southeast Con*. 441-445.

Gottlieb, M., Ireland, C.L.M. and Ley, J.M. (1983). *Electro-Optic and Acousto-Optic Scanning and Deflection*. New York: Marcel Dekker, Inc.

Goutzoulis, A.P., and Kludzin, V.V. (1994). *Principles of Acousto-Optics*. In Goutzoulis, A.P., and Pape, D.R.(Eds.) *Design and Fabrication Of Acousto Optic Devices*.(pp. 1-68). New York : Marcel Dekker, Inc.

Goutzoulis, A.P., and Pape, D.R.(Eds.) *Design and Fabrication Of Acousto Optic Devices*. New York : Marcel Dekker. Inc.

Harris Corporation. (1996). *Acousto-Optic Devices Technology: Basic Principles*. In Berg, N.J., and Pellegrino, J.M. (Eds.) *Acousto-Optic Signal Processing Theory and Implementation*. (pp. 21-36). New York : Marcel Dekker, Inc.

HD Communications Corp. (2001). *200 Watts Power Amplifier 0.15-230 MHz Model HD14975*. New York : Operating and Service Manual

Jabczynski, J.K., Zendzian, W., and Kwiatkowski, J. (2006). Q-Switch Mode Locking With Acousto-Optic modulator in a Diode Pumped Nd: YVO_4 Laser. *Optic Express*, 14(6), 2184-2190.

Johnson, R.V. (1994). *Design of Acousto-Optic Modulators*. In Goutzoulis, A.P., and Pape, D.R.(Eds.) *Design and Fabrication Of Acousto Optic Devices*.(pp. 123-195). New York : Marcel Dekker, Inc.

Kalkur, T.S. (2005). *Rectifier and Filter Circuits*. In Whitaker, J.C. (Ed.). *The Electronics Handbook*. (2nd ed.) (pp. 1026-1031) U.S.A : Taylor & Francis Group.

Kobayashi, N., and Amano, S. (1988). *U.S. Patent No. 4,792,93*0. : U.S. Patent and Trademark Office

Koechner, W. (2006), *Solid State Laser Engineering*. (6th ed.) New York: Springer-Verlag.

Korpel, A. (1981). Acousto-Optic –A Review of Fundamentals. *Proceedings of IEEE*. 69(1), 48-53.

Levi, L. (1980). *Applied Optics: A Guide to Optical System Design*. (2nd ed). New York: John Wiley & Sons, Inc.

Luxon, J.T. and Parker, D.E. (1992). *Industrial Laser and Their Applications*. (2nd ed). New Jersey: Prentice Hall, Inc.

LT-Pyrkal CISC. (2002). *AOML-50*. Armenia.: Operating Manual

Mattmuller, M.S. (2005). *Voltage Regulation*. In Whitaker, J.C. (Ed.). *The Electronics Handbook*. (2nd ed.) (pp.1031-1045). U.S.A: Taylor & Francis Group.

Maydan, D. (1970). Acoustooptical Pulse Modulators. *IEEE Jurnal of Quantum Electronics*. 6(1), 15-24.

Meade, R.L., and Diffenderfer, R. (2003). *Foundations of Electronic Circuit and Devices*. (4th ed.) New York: Delmar Learning.

Microchip Technology Inc. (2001). *PIC16F84A Data Sheet*. U.S.A: Datasheet.

Myslinski,P. (1986). Integrated Acousto-Optic Mode Locker. *Rev. Scl. Instrum*. 57(11), 2900-2901.

Glotz, M., and Eichler, H.J. (1987).Cavity Dumping of a Mode-Locked Pulsed Nd: YAG Laser. *J.Physics. E: Sci. Instrum*. 20, 1493-1496.

Gordon, E.I. (1966). A Review of Acoustooptical Deflection and Modulation Devices. *Proceedings of IEEE*. 54(10), 1391-1400.

McNeill, M.D., Poon, T., and Moore, D. (1994). *Pulse-Width Modulation using an Acousto-Optic Modulator*. Unpublished note,Virginia Polytechnic Institute and State University.

National Semiconductor. (2000a). *LM35 Precision Centigrade Temperature Sensors*. U.S.A: Datasheet.

National Semiconductor. (2000b). *LM129/LM329 Precision Reference*. U.S.A: Datasheet.

Neos Technologies. (2006). *Acousto-Optic Mode Locker*. U.S.A: Operating Manual.

Noriah Bidin. (2002). *Teknologi Laser*. Penerbit Universiti Teknologi Malaysia: Johor.

Ophir Optronic Ltd. (2002). *BeamStar, CCD Laser Beam Profiler for Windows*. Jerusalem: User Manual.

Pape, D.R., Gusev, O.B., Kulakov, S.V., and Molotok, V.V. (1994). *Design of Acousto-Optic Deflectors*. In Goutzoulis, A.P., and Pape, D.R.(Eds.) *Design and Fabrication Of Acousto-Optic Devices*.(pp. 69-122). New York : Marcel Dekker.

Pfaff, A. (1999). *Pulse Generators*. In Coombs, C.F. Jr. (Ed.). *Electronic Instrument Handbook*. (3rd ed.) (pp. 17.1-17.11). U.S.A: McGraw-Hill.

Pinnow, D.A. (1970). Guide Lines for the Selection of Acoustooptic Material. *IEEE Journal of Quantum Electronic*. 6(4) 223-238.

Pollack, S.E. (2002). *An Introduction to Acousto-Optics*. Unpublished note, University of Colorado.

Prosser, T.F. (1966). An Integrated Temperature Sensor-Controller. *IEEE Journal of Solid-State Circuits*. 1(1), 8-13.

Quate, C.F., Wilkinson, C.D.W., and Winslow, D.K. (1965). Interaction of Light Wave and Microwave Sound. *Proceeding of the IEEE*. 53(10), 604-1623.

Quimby, R.S. (2006). *Photonics and Lasers: An Introduction*. U.S.A: John Wiley & Sons, Inc.

Ready, J.F. (1978). *Industrial Application of Lasers*. New York: Academic Press.

Rhodes, W.T. (1981). Acousto-optic Signal Processing: Convolution and Correlation. *Proceeding of the IEEE*. 69(1), 65-79.

Saleh, B.E.A., and Teich, M.C. (1991). *Fundamentals of Photonics*. U.S.A: John Wiley & Sons, Inc.

Sapriel, J. (1979). *Acousto-Optics*. New York: John Wiley & Sons, Inc.

Scruby, C.B., and Drain L.E. (1990). *Laser Ultrasonic: Technique and Applications*. New York: Adam Hilger.

ST Microelectronics. (2003). *L165 Datasheet*. U.S.A: Datasheet.

Stevens, D. (2001). *The Role of Adaptive Photorefractive Power Limiting on Acousto-Optic RF Signal Excision*. Doctor Philosophy, University of Dayton, Ohio.

Thurlby Thandar Instruments. (2003). *TGR 1040 1GHz Synthesised RF Signal Generator*. England: Instruction Manual.

Thorlabs, Inc. (2006). *PDA36A*. New Jersey: Operating Manual.

Torrieri, D.J. (1996). *Introduction to Acousto-Optic Interaction Theory*. In Berg, N.J., and Pellegrino, J.M. (Eds.) *Acousto-Optic Signal Processing Theory and Implementation* (pp. 3-20). New York : Marcel Dekker.

Vanderlugt, A. (1991). *Optical Signal Processing*. New York: John Wiley & Sons, Inc.

White, D. (2005). *Shielding and EMI Considerations*. In Whitaker, J.C. (Ed.). *The Electronics Handbook*. (2^{nd} ed.) (pp. 1316-1352). U.S.A: Taylor & Francis Group.

Yariv,A. and Yeh, P. (1984). *Optical Waves in Crystals*. New York :John Wiley & Sons, Inc.

Young, E.H. and Yao, S.K. (1981). Design Considerations for Acousto-Optic Devices. *Proceedings of the IEEE*.69 (1), 54-64.

Zong, J. (1999). *Conversion Efficiency Improvement in an Acousto-Optical Modulator*. Doctor Philosophy, University of Arizona, Arizona.