# ADDIS ABABA UNIVERSITY
# DEPARTMENT OF PHYSICS

## OPTICALLY INDUCED BISTABILITY AS NONLINEAR OPTICS PHENOMENA

By
**YASABU AYALL**

A PROJECT SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES, ADDIS ABABA UNIVERSITY

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
AT
ADDIS ABABA UNIVERSITY
ADDIS ABABA, ETHIOPIA
May 2013

ADDIS ABABA UNIVERSITY
DEPARTMENT OF
PHYSICS

The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance a project entitled " OPTICALLY INDUCED BISTABILITY AS NONLINEAR OPTICS PHENOMENA" by **YASABU AYALL** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: May 2013

Advisor: ______________________
Prof. Mal'nev V.

Examiner: ______________________

ADDIS ABABA UNIVERSITY

Date: **May 2013**

Author: **YASABU AYALL**

Title: **OPTICALLY INDUCED BISTABILITY AS NONLINEAR OPTICS PHENOMENA**

Department: **Physics**

Degree: **M.Sc.** Convocation: **May** Year: **2013**



______________________________

Signature of Author

# Contents

# List of Figures



▽

# Acknowledgements

Above all,I would like to thank the almighty God. Then I offer my deepest gratitude to my beloved advisor and instructor Prof. Mal'nev V. for his unlimitted guidance, assistance, supervision and contribution of valuable suggestions.Next I would like to thank my dear family and all those persons who help me.

## Abstract

The project is devoted to a review of some manifastations of the nonlinear optics phenomena. In the first chapter of this project, we will see the brief introduction of nonlinear optics like nonlinear optical phenomena,nonlinear optical material and thier properties,polarization of nonlinear optics and thier wave equation. The second chapter of this project deal with physical origin of NLO phenomena and futurity of NLO. chapter three of this project about optically induced bistability and Chapter four is about thier application of NLO.

# Chapter 1

# Introduction

Nonlinear optics (NLO) is the study of the interaction of intense laser light with matter [1]. Nonlinear optics is the branch of optics that explores the coherent coupling of two or more electromagnetic fields. In these processes, new field components are generated at frequencies that are either the sum or difference of the coupling fields [2], [3].

Nonlinear optics has a wide range of application in many areas such as communication and optical computing of particular interest. We can use nonlinear optical materials to achieve all optical control of electromagnetic waves which can lead to all optical signal processing. Nonlinear optics also has a number of inherent benefits such as the ability to compensate. For linear dispersion and spatial solitons utilizing the nonliear properties of various materials, optical switches and modulators have also been realilized and found wide application in modern telecomunication industries. All optical logic is to take advantage of the property of nonlinear materials where transverse electric (TE) and transverse magnetic (TM) polarizations can exchange energy when they are present simultaneously. This nonlinear coupling between TE and TM polarization is unidirectional in planar semiconductor wave guides i.e., the electromagnetic energy tends to transfer from TM to TE modes only. All optical logic gates based on four wave mixing have been shown and the discussion have mostly been limited to theoretical modeling and systems has been that the logic operation is necessarily done using light sources at multiple frequencies. Nonlinear optical (NLO) effects are analyzed by considering response of the electric fields of an intense light beam. The propagation of a wave through a material produces changes in the spatial and temporal distribution of electrical charges as the electron and atoms interact with the elecromagnetic fields of the wave. The main effect of the force exerted by the field on the charged particles is displacement of the valence electrons from their normal oribits. This perturbation creates elecrtic dipoles whose macroscopic manifestation is the polarization. Thus the polarization in nonliear and nonlinear optics (NLO) is the study of the intraction of intense electromagnetic field with material to produce magnetic fields that are differrent from the input field in phase, frequency or amplitude.

## 1.1 Concept of nonlinear optical phenomenon

While the first nonlinear effects were seen in the demonstration of harmonic generation in quartz, one of the most intensively studied nonlinear optical phenomenon and specifically the NLO property studied in the present paper is second harmonic generation. The electromagnetic waves propagated through a crystalline solid, which lacks a center of symmetry, generates light at second and higher harmonics of the applied frequency. These important nonlinear properties of NLO materials are usually divided into different classes that refer to the order of the nonlinear susceptibility that describes the response of the material, to the electric field associated with the light radiation. NLO materials are used for second harmonic generation. These materials must have an asymmetrical structure whose refractive index can also be controlled with an external electric field, a property that is referred to as the electro-optic effect. This property has the principal importance for many applications and is currently used in electro-optics modulators. It also plays a major role in the photo refractive effect. Materials are expected to play a key role in all optical switching devices since their optical properties can be controlled by light. However, due to the higher order of the nonlinearity these materials are usually less efficient and have not reached the maturity of materials for device applications.

## 1.2 Nonlinear optical materials

Nonlinear optical (NLO) materials have long been interact observed to with light to produce a nonlinear response and the development of new nonlinear optical materials of inorganic, organic and semi-organic types. Thus the optical nonlinearities of conjugated system have been widely studied in view of their potential applications in photonic and electro-optic devices( Marder et al 1991,Denning et al 2001). In organic NLO materials such as lithium niobate ($LiNbO_3$) or potassium dihydrogen phosphate($KH_2PO4$) are known to exhibit second harmonic generation(SHG) effect. Lithium niobate powders have attracted agreat deal of attention due to thier potential applications mainly because of its unique electro-optics, acousto-optic and nonlinear optical properties. Inorganic materials have been employed as optical materials and consequently these material have dominated optical technology. Organic nonlinear optical materials have been investigated due to their potentially high nonlinearities and rapid response in electro-optic effect compared to inorganic NLO materials. In case of organic crystals, two requirements are satisfied:

(i) They are made of highly polarizable molecules, the so-called conjugated molecules, where highly delocalized p-electrons can easily move between electron donor and electron acceptor groups on opposite sides of the molecule, inducing a molecular charge transfer.

(ii) The molecules are adequately packed to build up a noncentrosymmetrical crystal structure that provides nonvanishing second order nonlinear coefficients.

## 1.3 Properties of nonlinear optical materials

Nonlinear optical (NLO) materials play a major role in nonlinear optics and in particular they have agreat impact on information technology and industrials applications. The goal is to find and develop materials presenting large nonlinearities and satisifying at the same time all the technolgical requirment for applications such wide transparency range fast response high damage threshold but also processability adapitibility and interacting with other material. The advantages of nonlinear optics (NLO) over electronics materials for information manipulation include immunity from electromagnetic interference, elimination of electrical short circuits and ground loops, safety in combustible environments, low loss transmission, large band width, security from tapping, possibility of 3-dimensional integration of devices, small size and light weight, and inherent paralleled processing of data for orders of magnitude increase in computing power. In addition, NLO can significantly improve the performance and character of laser sources providing new capabilities such as:

1) wavelength conversion, offering new discrete wavelength lines and wavelength tunability over a much broader spectral range than is possible with chemical lasers,

2) amplification,

3) Q-switches for pulsed lasers (Q-switching is a technique by which a laser can be made to produce a pulsed output beam), and

4) optical phase conjugation for more ideal beam profiles and the coupling of laser beams.

Nonlinear optical responses are divided into second-order and third-order effects. In simple terms, a second-order material can be used for generating new laser wavelengths, for the photo refractive effect yielding improved laser beam profiles and distortion, correction and for electro optic effects for controlling light by electric fields from electronics. A third-order material can be used to control light by light for intrinsic limiters, for laser hardened optics and for all optical computing concepts.

The material properties of NLO materials are extremely demanding. The desirable properties include very large nonlinear optical responses, low power thresholds, fast switching speeds, high optical damage thresholds, low optical loss, thermal stability, temporal stability, and processability into optical quality films, fibers, and circuit components.

## 1.4 Polarization in nonlinear optics

When elecromagnetic wave(EMW) propagates through an optical medium, the oscillating electromagnetic field exerts polarizing forces on all of the electrons comprising the medium. since the inner electron of the atoms are tightly bound to the nuclei,the major polarizing effect is exerted on the outer or valence electrons. With ordinary light sources the radation fields are much smaller than the fields that bind the electrons to the atoms. Hence, the radiations acts as a small purturbation which produces a polarization that is proportional to the field, comparable with the atomic fields ( $10^8 V/cm$), the relation between the polarization and the radation field is no longer a linear one shown in fig.1.1. [4].

The requisite light fields needed to exhibit this nonlinearity are available laser sources. Non-

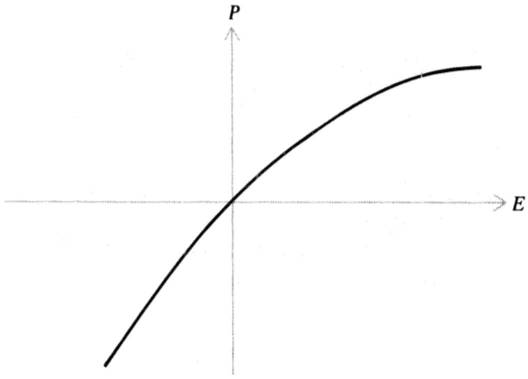



Figure 1.1: Curve of polarization versus electric field for a nonlinear dielectric.

linear optical effects that have been observed include optical rectification and many other. In an isotropic medium the general relation between the polarization P and electric field E is expressible as a simple series expansion involving only the magnitudes of the filed, since the direction of the polarization coincide with that of the field name.

$$P = \varepsilon_0(\chi^{(1)}E^{(1)} + \chi^{(2)}E^{(2)} + \chi^{(3)}E^{(3)} + ...), \tag{1.1}$$

$$P = P^{(1)}(t) + P^{(2)}(t) + P^{(3)}(t) + ... \tag{1.2}$$

The polarization at time $t$ depends on the value of the electric field strength. $P^{(1)}(t) = \epsilon_0\chi^{(1)}E^{(1)}(t)$ refers to the linear polarization ,$p^{(2)}(t) = \epsilon_0\chi^{(2)}E^{(2)}(t)$ to the second-order non-linear polarization and $P^{(3)}(t) = \epsilon_0\chi^{(3)}E^{(3)}(t)$ to the third-order nonlinear polarization. The expansion as the sum of two terms $P = P^L + P^{NL}$ from the above expression, where $\epsilon_0$ the free space permitivity and $\chi^{(1)}$, $\chi^{(2)}, \chi^{(3)}$... the first-order, second-order and third-order susceptibility of the medium.

The first order susceptibility represents linear property of the medium, if the light wave strength is relatively low. If electromagnetic wave strength is sufficiently high, the higher order susceptibilities given nonlinear effects.Those susceptibilities depend up on the molecular structure of the material. The electric field passing through the medium can be represented by

$$E = E_0 e^{-i\omega t}. \tag{1.3}$$

When the amplitude of the applied field ($E$) is the order of characteristics atomic electric field and it is given by $E_{at} = E_0 = \frac{e}{4\pi\epsilon_0 a_0^2}$. where $e$ is charge of electron and $a_0 = 0.529\mathring{A}$ is Bohr radius of the hydrogen atom and the numerical value of $E_0$ is $5.14 \times 10^{11}\frac{V}{m}$ and the induced polarization is must account of the nonlinear terms

$$P = \epsilon_0(\chi^{(1)} E_0 e^{-i\omega t} + \chi^{(2)} E_0^2 e^{-i2\omega t} + \chi^{(3)} E_0^3 e^{-i3\omega t} + ... + c.c). \tag{1.4}$$

where c.c stands for complex conjugate. The part of the polarization associated with the second and higher terms gives rise to the generation of optical harmonics.

## 1.5 Comparison of linear optics and nonlinear optics

Here let us compare linear and nonlinear optics.

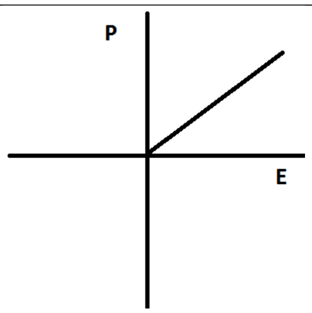
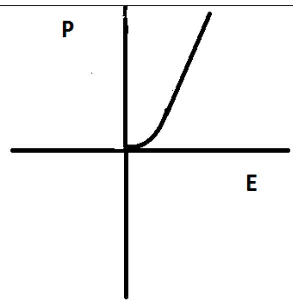
| Linear optics | Nonliear optics |
|---|---|
| P=$\epsilon_{(0)}\chi^{(1)}E^{(1)}$<br>where $\chi^{(1)}$ linear susceptibility | $P = \epsilon_{(0)}\chi^{(2)}E^{(2)} + \epsilon_{(0)}\chi^{(3)}E^{(3)} + ...$<br>where$\chi^{(2)}$,$\chi^{(3)}$,... $n^{th}$ order of nonlinear susceptibilities |
| The magnitude of electric field is small | The magnitude of electric field is large |
| Light is deflected or delayed but its frequency is unchanged | Light itself induced as it propagate through medium |
| The principle of Superposition is valid | The principle of Superposition is not valid |
| <br>The graph of polarization versus electric field in case of linear optics | <br>The graph of polarization versus electric field in case of nonlinear optics |

Table 1.1: Comparison of linear optics with nonliear optics.

## 1.6 Wave equation in a nonlinear material

Central to the study of electromagnetic waves is the wave equation. Starting with Maxwell's equations in an isotropic space containing no free charge, it can be shown that:

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{n^2 \partial^2 \mathbf{E}}{c^2 \partial t^2} = -\frac{1}{\varepsilon_0 c^2} \frac{\partial^2 P^{NL}}{\partial t^2}, \tag{1.5}$$

where $P^{NL}$ is the nonlinear part of the Polarization and $n$ is the refractive index which comes from the linear term in $P$. Note that one can normally use the vector identity:

$$\nabla \times (\nabla \times \mathbf{V}) = \nabla(\nabla \cdot \mathbf{V}) - \nabla^2 \mathbf{V}, \tag{1.6}$$

and Gauss's law,

$$\nabla \cdot \mathbf{D} = 0, \tag{1.7}$$

to obtain the more familiar wave equation

$$\nabla^2 \mathbf{E} - \frac{n^2 \partial^2 \mathbf{E}}{c^2 \partial t^2} = 0, \tag{1.8}$$

For nonlinear medium Gauss's law does not imply that the identity

$$\nabla \cdot \mathbf{E} = 0, \tag{1.9}$$

is true in general, even for an isotropic medium. However even when this term is not identically 0, it is often negligibly small and thus in practice is usually ignored giving us the standard nonlinear wave equation:

$$\nabla^2 . \mathbf{E} - \frac{n^2 \partial^2 \mathbf{E}}{c^2 \partial t^2} = -\frac{\partial^2 P^{NL}}{\varepsilon_0 c^2 \partial t^2}. \tag{1.10}$$

### 1.6.1 Nonlinearities as a wave mixing process

The nonlinear wave equation is an inhomogeneous differential equation. The general solution comes from the study of ordinary differential equations and can be solved by the use of a Green's function. Physically one gets the normal electromagnetic wave solutions to the homogeneous part of the wave equation:

$$\nabla^2 \mathbf{E} - \frac{n^2 \partial^2 \mathbf{E}}{c^2 \partial t^2} = 0. \tag{1.11}$$

and the inhomogenous term $\frac{1}{\varepsilon_0 c^2}\frac{\partial^2 P^{NL}}{\partial t^2}$ acts as a driver/source of the electromagnetic waves. One of the consequences of this is a nonlinear interaction that will result in energy being mixed or coupled between different frequencies, which is often called a 'wave mixing'. In general an $n^{th}$ order nonlinearity will lead to $n+1^{th}$ wave mixing. As an example, if we consider only a second-order nonlinearity (three-wave mixing), then the polarization $P$ takes the form of

$$P^2 = \epsilon_0 \chi^2 E^2(t). \tag{1.12}$$

If we assume that E(t) is made up of two components at frequencies $\omega_1$ and $\omega_2$, we can write E(t) as

$$E(t) = E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c, \tag{1.13}$$

Inserting this into equation (1.12) the second-order nonlinear polarization gives

$$\begin{aligned} p^2 &= \epsilon_0 \chi^2 E^2(t), \\ &= \epsilon_0 \chi^2 (E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c)^2, \\ &= \epsilon_0 \chi^2 [|E_1|^2 e^{-i2\omega_1 t} + |E_2|^2 e^{-i2\omega_2 t} + 2E_1E_2 e^{-i(\omega_1+\omega_2)t} + \\ &\quad 2E_1E_2 e^{-i(\omega_1-\omega_2)t} + 2(|E_1|^2 + |E_2|^2)]. \end{aligned} \tag{1.14}$$

which has frequency components at $2\omega_1, 2\omega_2, \omega_1+\omega_2, \omega_1-\omega_2$, and 0. These three wave mixing processes correspond to the nonlinear effects known as second harmonic generation, sumf-requency generation, difference-frequency generation and optical parametric generation respectively [1],[4].

### 1.6.2 Second-harmonic generation

Second-harmonic generation, is a nonlinear process where photon at a frequency $2\omega$ is generated from the interaction between intense light at frequency $\omega$ and nonlinear medium. The process occurs with in a nonlinear medium usually a crystal,where the light generates light at second and higher harmonics of the applied frequency. Such frequency doubling are commonly used to produce green light with a wavelength of 532 nm from laser operating at 106 4nm. This important nonlinear property in noncentrosymmetric crystals is called second-harmonic generation.

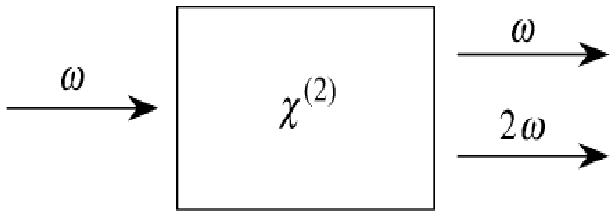



Figure 1.2: Second-harmonic generation

### 1.6.3 Sum-frequency generation

Sum-frequency generation (SFG) is a nonlinear optical process in which from two input photons of low energy incident on nonlinear medium, a new high energy photon can be generated. If an incident intense optical field contains two monochromatic components of frequency $\omega_1, \omega_2$ and propagate through a second-order nonlinear crystal, a coherent radiation at the sum-frequency of $\omega_3 = \omega_1 + \omega_2$ may be obtained.

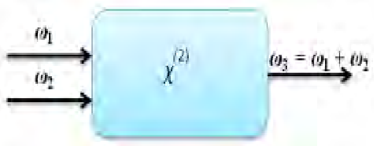



Figure 1.3: Geometry of the sum-frequency generation

### 1.6.4 Difference frequency generation.

It is a generation of light with frequancy that is the difference between two frequencies.

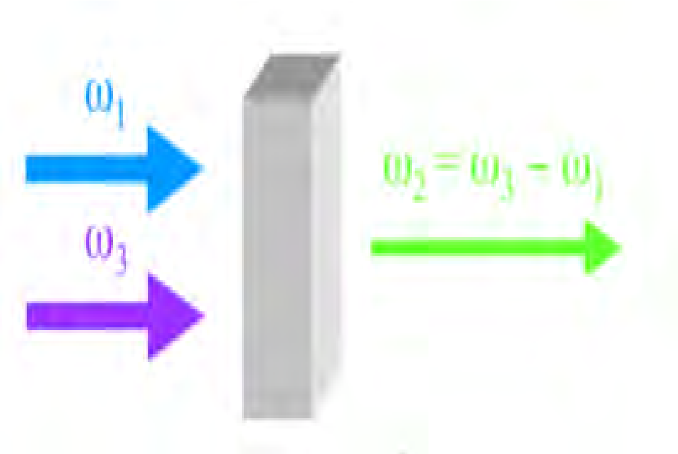



Figure 1.4: Difference frequence generation.

### 1.6.5 Optical parametric generation

We have just seen that in the process of difference-frequency generation the presence of radiation at frequency $\omega_2$ or $\omega_3$ can stimulate the emission of additional photons at these frequencies. If the nonlinear crystal used in this process is placed inside an optical resonator, as shown in Fig. 1.5, the $\omega_2$ and/or $\omega_3$ fields can build up to large values. The applied field frequency $\omega_3$ is often called the pump frequency, the desired out-put frequency $\omega_1$is called the signal frequency, and the other, unwanted, output frequency $\omega_3$ is called the idler frequency.

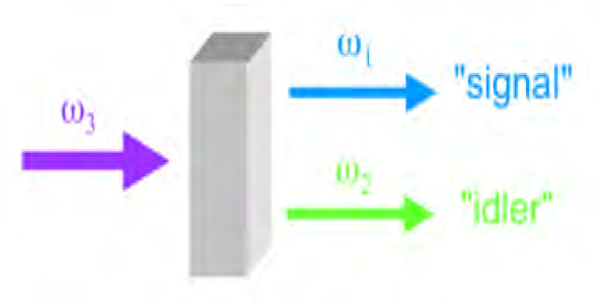



Figure 1.5: Optical parametric generation.

# Chapter 2

# THEORETICAL FUNDAMENTALS OF NONLINEAR OPTICS

The explanation of nonlinear optics effects in the way in which a beam of light propagates through asolid. The nuclei and associated elecctrons of atoms in the solid form an electric dipole. The electromagnetic radiation interacts with the dipoles causing them to oscillate which by the classical laws of electromagnetic radiation. If the amplitude of elecromagnetic radiation increases, the relationship between irradiance and amplitude of vibration becomes nonlinear resulting in the generation of harmonic radiation emitted by the oscillating dipoles. Thus frequency doubling or second-harmonic generation (SHG ) and indeed higher order frequency effects occurs as the induced polarization is a nonlinear function of the applied field. A medium exhibiting (SHG) is a crystal in such away that a polar orintation is maintained throughout the crystals [11].

## 2.1 Physical origins of NLO phenomena

The physical origins of NLO phenomena can be categorized as either structural or compositional. Here structural refers to light induced structure changes, such as the change of electronic density, average interatomic distances, molecular orientation, phase transition, etc. These phenomena belong to the intrinsic category. A light-induced chemical composition change can be classified as the extrinsic type. The phenomenon consists essentially of light-induced chemical reactions (such as molecular dissociation, polymerization, and transformation). It can be reversible or permanent.

### 2.1.1 Electronic nonlinearity

When off-resonance, the electronic nonlinearity arises from hyperpolarizable, delocalized electrons. The electronic structure change is the distortion of electronic clouds. It gives the fastest response time (of the order of femtoseconds). Under resonant conditions, the electronic structure change is the distribution of electrons at different electronic states. The nonlinearity can be enhanced by several orders of magnitude by sacrificing response time and absorption loss.

### 2.1.2 Thermal nonlinearity

Although thermal nonlinearity has been used as the basis for the construction of temperature and chemical sensors, it is not desirable for many applications. It occurs in resonant NLO interactions due to the absorption of light and the generation of phonons. In some cases, the nonlinear response can be tremendous. For example, in the thermal elasto-optical effect in absorbing organic polymers, or in the thermally induced solid, liquid transition in liquid-crystal systems.

### 2.1.3 Orientational nonlinearity

Orientational nonlinearity can be explained as follows: in OKE or DFWM experiments, when using polarization modulation, the molecules possessing permanent electric dipoles can be aligned along the strong optical field of the orthogonally polarized light, or molecules without permanent dipoles are aligned through the induced dipoles. The nonlinear response arises from the orientational anisotropic properties, i.e., the birefringence when off-resonance and, additionally, dichroism on resonance.

## 2.2 Future of nonlinear optics

Future technological development should be based on current science. All-optical picosecond ($10^{-12}s$) switching and quantum logic with entangled states has been demonstrated. Entangled states of two photons are produced, for example, by parametric down conversion of coherent beam or by entangled polarization of two photons emitted in a state to state transition. Entangled one photon, one atom states have been achieved by Haroche et al [5] .

One may envision ultrafast optical supercomputers based on these developments. Two dimensional (2-D) and three dimensional (3-D) photonic band gap materials may be helpful in the manipulation of light beams in all-optical or integrated optical electronic switching devices.

Three-dimensional holographic information storage has been around for several decades but has yet to achieve large-scale applications. The optical storage of compact disks could be extended to several layers in the perpendicular direction. Fluorescence from centers activated by absorption of two photons from different beams or submicroscopic damage spots from strongly focused femtosecond pulses could, in principle, lead to high density storage of bits of information.

Tajima and Dawson [6] proposed the acceleration of relativistic electrons in the wake field of space charges in plasmas created by laser pulses with large spatial and temporal gradients. The technological development of powerful femtosecond pulse generators may lead to a new type of electron accelerator. Such devices would be much more compact and presumably cheaper than an extension of the current linear accelerator [7] , [8]. High power femtosecond laser pulses can propagate in the atmosphere over considerable distances [9].

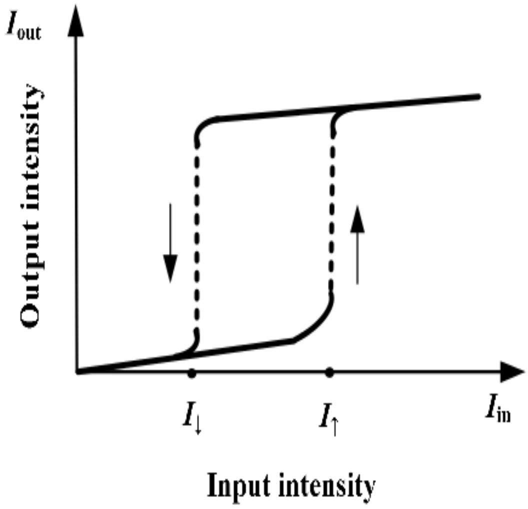
The field of nonlinear optics is alive and well and has grown much beyond our expectations of three or four decades ago. We believe it will continue to exceed our current expectations in the future.

# Chapter 3

# OPTICALLY INDUCED BISTABILITY

Optical bistability is the situation in which two different output intensities are possible for a given input intensity, and the more general term optical multistability is used to describe the circumstance in which two or more stable output states are possible [1]. Optical bistability is a well known phenomenon in which absorption or dispersion in a medium in a resonator induces an optical path length change that is proportional to the intra-cavity light intensity in such a way that cavity transmission exhibits more than one stable operating point. Induced optical bistability (IOB) means that some nonlinear optical systems can produce two different output intensities for a given input intensity [1] or, in particular, the given value of an external electric field may produce several values for the local field and the polarization. This effect has been intensively studied because of its potential use for optical switching devices and in optical computing [27−29].

Optical bistability was first described theoretically and observed experimentally using an absorptive nonlinearity by Szöke et al. (1969) [25]. Optical bistability was observed experimentally for the case of a refractive nonlinearity (real $\chi^3$ )by Gibbs et al. (1976) [24].




bi.png

Figure 3.1: Characteristics curve for a bistable system

The bistable optical device described in these works consists of a nonlinear medium placed inside of a Fabry Perot resonator[1]. Such a device is illustrated schematically in Fig.3.2

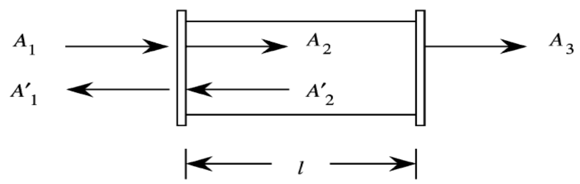



Figure 3.2: Bistable optical device in the form of a Fabry Prot interferometer containg a nonlinear medium.

Here $A_1$ denotes the field amplitude of the incident wave, $A_1'$ denotes that of the reflected wave,$A_2$ and $A_2'$ denote the amplitudes of the forward and backward going waves within the interferometer, and $A_3$ denotes the amplitude of the transmitted wave. The cavity mirrors are assumed to be identical and lossless, with amplitude reflectance $\rho$ and transmittance $\tau$ that are related to the intensity reflectance $R$ and transmittance $T$ through

$$R = |\rho|^2 \qquad and \qquad T = |\tau|^2, \tag{3.1}$$

with

$$R + T = 1. \tag{3.2}$$

The incident and internal fields are related to each other through boundary conditions of the form

$$A_2' = \rho A_2 e^{2ikl - \alpha l}, \tag{3.3}$$

$$A_2 = \tau A_1 + \rho A_2'. \tag{3.4}$$

In these equations, we assume that the field amplitudes are measured at the inner surface of the left-hand mirror. The propagation constant $k = \frac{n\omega}{c}$ and intensity absorption coefficient $\alpha$ are taken to be real quantities, which include both their linear and nonlinear contributions. In writing Eqs. (3.3) and (3.4) in the form shown, we have implicitly made a mean field-approximation that is,assumed; that is the quantities $k$ and $\alpha$ are spatially invariant. For simplicity we also assume that the nonlinear material and the medium surrounding the resonator have the same linear refractive indices. $A_2$ can be solved by substitute equation (3.3) in to equation (3.4)

$$A_2 = \tau A_1 + \rho^2 A_2 e^{2ikl - \alpha l},$$

$$A_2 - \rho^2 A_2 e^{2ikl - \alpha l} = \tau A_1,$$

$$A_2 (1 - \rho^2 e^{2ikl - \alpha l}) = \tau A_1,$$

$$A_2 = \frac{\tau A_1}{1 - \rho^2 e^{2ikl - \alpha l}}, \tag{3.5}$$

Equation (3.5) describes the properties of a Fabry-Perot interferometer. If $k$ or $\alpha$ (or both) is a sufficiently nonlinear function of the intensity of the light within the interferometer, this equation predicts bistability in the intensity of the transmitted wave. In general, both k and $\alpha$ can display nonlinear behavior; however, we can obtain a better understanding of the nature of optical bistability by considering in turn the limiting cases in which either the absorptive or the refractive contribution dominates.

## 3.1 Different types of optical bistability

The nature of optical bistability is either absorptive optical bistability or refractive optical bistability.

### 3.1.1 Absorptive optical bistability

Absorptive optical bistability is based upon coupling the feedback mechanism inherent in an optical cavity with an absorbing nonlinear optical medium in which the absorption coefficient decreases with increasing light intensity (a saturable absorber). The basic theory of operation is: the saturable absorber is placed in the cavity, and the cavity is resonantly pumped. For low light intensities, the transmission coefficient for the cavity is small because of the presence of the highly absorbing medium inside the cavity. As the pump intensity is increased, the absorption of the nonlinear medium decreases. Finally, for some threshold pump intensity, the cavity switches into a high transmission state, because the absorption coefficient is reduced sufficiently that the intrinsic cavity feedback mechanism dominates. The threshold is very sharp because, when the cavity is in a highly transmittive state, the built up intensity inside the cavity becomes very large compared to the pump intensity (due to the feedback) and effectively bleaches virtually all of the absorption in the nonlinear medium. The intense pump is then largely transmitted, although some energy is stored in the cavity to bleach the absorber [1], [9]. Let us first examine the case in which only the absorption coefficient $\alpha$ depends nonlinearly on the field intensity. The wave vector magnitude $k$ is hence assumed to be constant. To simplify the following analysis, we assume that the mirror separation $l$ in Fig.3.2 is adjusted so that the cavity is tuned to resonance with the applied field; in such a case the factor $\rho^2 e^{2ikl}$ that appears in the denominator of Eq. (3.5) is equal to the real quantity $R$. We also assume that $\alpha l << 1$, so that we can ignore the spatial variation of the intensity of the field inside the cavity, which justifies the use of the mean field-approximation. Under these conditions equation (3.5) reduces to

$$A_2 = \frac{\tau A_1}{1 - \rho^2 e^{2ikl - \alpha l}},$$

$$A_2 = \frac{\tau A_1}{1 - \rho^2 e^{2ikl} e^{-\alpha l}},$$

$$A_2 = \frac{\tau A_1}{1 - Re^{-\alpha l}},$$

where $e^{-\alpha l} \approx 1 - \alpha l$ ,

$$A_2 = \frac{\tau A_1}{1 - R(1 - \alpha l)}. \tag{3.6}$$

The analogous equation relating the incident and circulating intensities $I_i = 2n\epsilon_0 c|A_i|^2$ is given by

$$I_2 = \frac{2n\epsilon_0 |\tau|^2 |A_1|^2}{[1 - R(1 - \alpha l)]^2}$$

but $I_1 = 2n\epsilon_0|A_1|^2$

$$I_2 = \frac{TI_1}{[1 - R(1 - \alpha l)]^2} \tag{3.7}$$

Equation(3.7) is can be simplified by introducing the dimensionless parameter $C$ which is known as the cooperation number,

$$C = \frac{R\alpha l}{1 - R} \tag{3.8}$$

$$1 + C = 1 + \frac{R\alpha l}{1 - R},$$

$$= \frac{(1 - R) + R\alpha l}{1 - R},$$

$$= \frac{[1 - R(1 - \alpha l)]}{T},$$

since $1 - R = T$

$$(1 + C)(T) = 1 - R(1 - \alpha l)$$

$$I_2 = \frac{I_1}{T(1 + C)^2}. \tag{3.9}$$

We now assume that the absorption coefficient $\alpha$ and hence the parameter $C$ depend on the intensity of the light within the interferometer. For simplicity, we assume that the absorption coefficient obeys the relation valid for a two level saturable absorber,

$$\alpha = \frac{\alpha_0}{1 + \frac{I}{I_s}}. \tag{3.10}$$

where $\alpha_0$ denotes the unsaturated absorption coefficient, $I$ the local value of the intensity, and $I_s$ the saturation intensity. For simplicity we also ignore the standing-wave nature of the field within the interferometer and take $I = I_2 + I_2' \approx 2I_2$. It is only approximately valid to ignore standing wave effects for the interferometer of Fig. 3.2, but it is strictly valid for the traveling wave interferometer shown in Fig 3.3 . Under the assumption that the absorption coefficient depends on the intensity of the internal fields according to the input-output relation implied

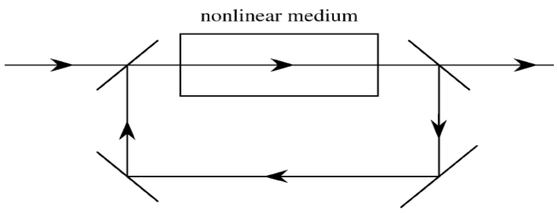



Figure 3.3: Bistable optical device in the form of a traveling wave interferometer containing a nonlinear medium.

by Equation (3.10) with $I = 2I_2$, the parameter $C$ is given by:-

$$C = \frac{C_0}{1 + \frac{2I_2}{I_s}} \tag{3.11}$$

where $C_0 = \frac{R\alpha_0 l}{1-R}$ . The relation between $I_1$ and $I_2$ given by Eq. (3.9) can be rewritten using this expression for $C$ as

$$I_1 = TI_2(1 + \frac{C_0}{1 + \frac{2I_2}{I_s}})^2 \tag{3.12}$$

Finally, the output intensity $I_3$ is related to $I_2$ by

$$I_3 = TI_2 \tag{3.13}$$

for several different values of the weak-field parameter $C_0$ . For $C_0$ greater than 8, more than one output intensity can occur for certain values of the input intensity, which shows that the system possesses multiple solutions. The input-output characteristics for a system showing optical bistability are shown schematically in Fig. 3.5 (a). The portion of the curve that has

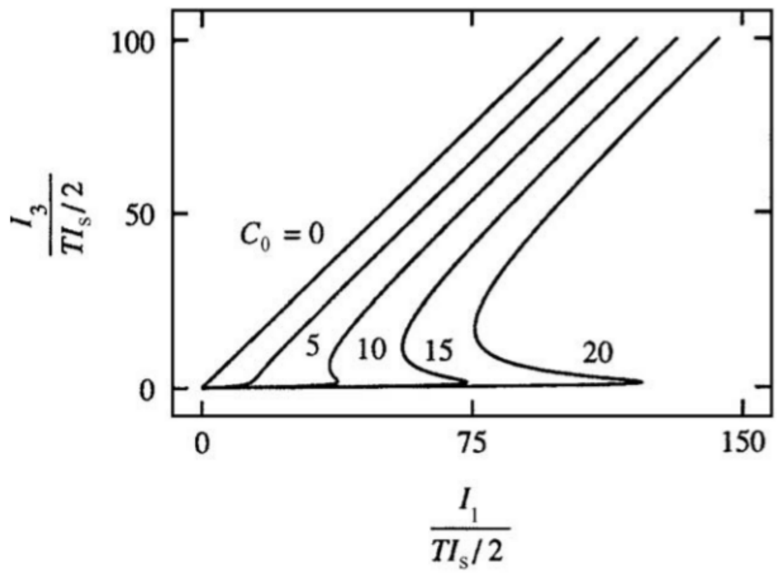



Figure 3.4: The input-output relation for a bistable optical device described by eq (3.12)and (3.13)

a negative slope is shown by a dashed line. This portion corresponds to the branch of the solution to Eq. (3.12) for which the output intensity increases as the input intensity decreases. As might be expected on intuitive grounds, and as can be verified by means of a linear stability analysis, this branch of the solution is unstable; if the system is initially in this state, it will rapidly switch to one of the stable solutions through the growth of small perturbations. The solution shown in Fig. 3. 5 (a) displays hysteresis in the following sense. We imagine that the input intensity $I_1$ is initially zero and is slowly increased. As $I_1$ is increased from zero to $I_h$ (the high jump point), the output intensity is given by the lower branch of the solution, that is, by the segment terminated by points $a$ and $b$. As the input intensity is increased still further, the output intensity must jump to point $c$ and trace out that portion of the curve labeled $c - d$. If the intensity is now slowly decreased, the system will remain on the upper branch and the output intensity will be given by the curve segment $e-d$ . As the input intensity passes through the value $I_l$ (the low jump point), the system makes a transition to point $f$ and traces out the

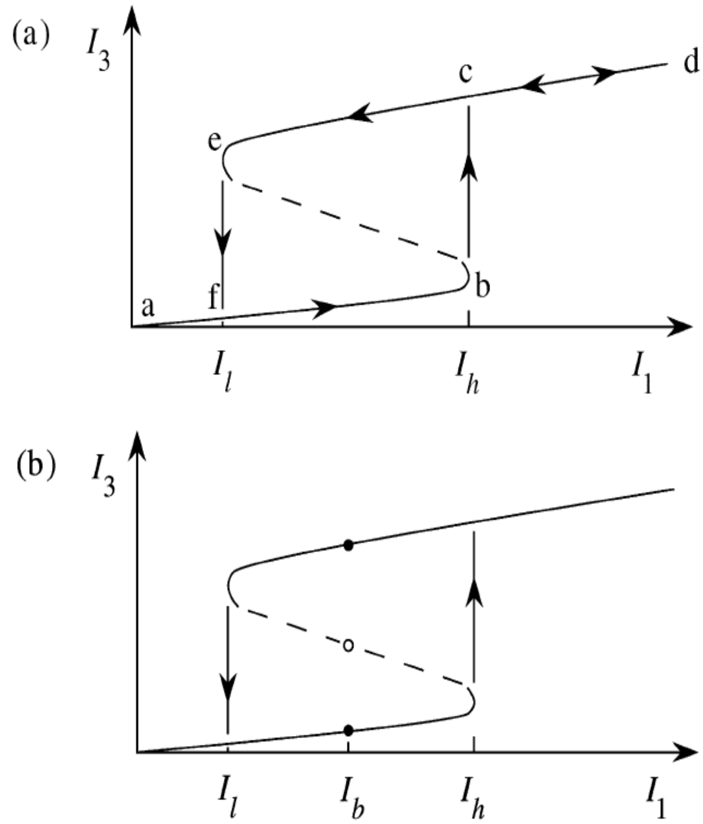



Figure 3.5: Schematical representation of input-output characteristics for a system showing optical bistability.

curve of $f - a$ as the input intensity is decreased to zero. The use of such a device as an optical switch is illustrated in part (b) of Fig. 3.5. If the input intensity is held fixed at the value $I_b$ (the bias intensity), the two stable output points indicated by the filled dots are possible. The state of the system can be used to store binary information. The system can be forced to make a transition to the upper state by injecting a pulse of light so that the total input intensity exceeds $I_h$; the system can be forced to make a transition to the lower state by momentarily blocking the input beam.

### 3.1.2 Refractive Optical bistability

Refractive optical bistability is based on coupling the feedback mechanism inherent in an optical cavity with a nonlinear optical medium that exhibits a change in the refractive index as a function of light intensity. The nonlinear refractive medium is placed inside the optical cavity, and the cavity is pumped slightly off-resonance so that the transmission coefficient is small compared to unity. However, a small amount of light intensity does exist inside the cavity, and changes the effective optical path length inside the cavity by inducing change in the refractive index of the nonlinear medium. Let us now consider the case in which the absorption coefficient vanishes but in which the refractive index $n$ depends nonlinearly on the optical intensity. For $\alpha = 0$, Eq. (3.5) becomes

$$A_2 = \frac{\tau A_1}{1 - \rho^2 e^{2ikl}},$$

$$A_2 = \frac{\tau A_1}{1 - R e^{2ikl}},$$

$$A_2 = \frac{\tau A_1}{1 - R e^{i\delta}}, \tag{3.14}$$

In obtaining the second form of this equation, we have written $\rho^2$ in terms of its amplitude and phase as

$$\rho^2 = R e^{i\phi}, \tag{3.15}$$

and have introduced the total phase shift $\delta$ acquired in a round trip through the cavity. This phase shift is the sum

$$\delta = \delta_0 + \delta_2, \tag{3.16}$$

of a linear contribution

$$\delta_0 = \phi + 2n_0\frac{\omega}{c}L \tag{3.17}$$

and a nonlinear contribution

$$\delta_2 = 2n_2 I\frac{\omega}{c}L \tag{3.18}$$

Equation (3.14) can be used to relate the intensities $I_i = 2n\epsilon_0|A_i|^2$ of the incident and internal fields as;

$$I_2 = 2n\epsilon_0|A_2|^2,$$

$$I_2 = \frac{2n\epsilon_0 C\tau^2|A_1|^2}{(1-Re^{i\delta})^2},$$

$$I_2 = \frac{I_1 T}{(1-Re^{i\delta})(1-Re^{-i\delta})},$$

$$I_2 = \frac{I_1 T}{1-R(e^{i\delta}+e^{-i\delta})+R^2},$$

$$I_2 = \frac{I_1 T}{1+R^2-2Rcos\delta}, \tag{3.19}$$

since $e^{i\delta}+e^{-i\delta} = 2cos\delta$ and from double angle formula $cos\delta = 1-2sin^2\frac{\delta}{2}$,

$$I_2 = \frac{I_1 T}{1+R^2-2R+4Rsin^2\frac{\delta}{2}},$$

$$I_2 = \frac{I_1 T}{(1-R)^2+4Rsin^2\frac{\delta}{2}},$$

$$I_2 = \frac{I_1 T}{(T)^2+4Rsin^2\frac{\delta}{2}},$$

$$I_2 = \frac{\frac{I_1}{T}}{1+\frac{4R}{T^2}sin^2\frac{\delta}{2}}.$$

$$\frac{I_2}{I_1} = \frac{\frac{1}{T}}{1 + \frac{4R}{T^2} sin^2 \frac{\delta}{2}} \tag{3.20}$$

The solution of equation (3.20) can be solved graphically. The oscillatory curve represents the

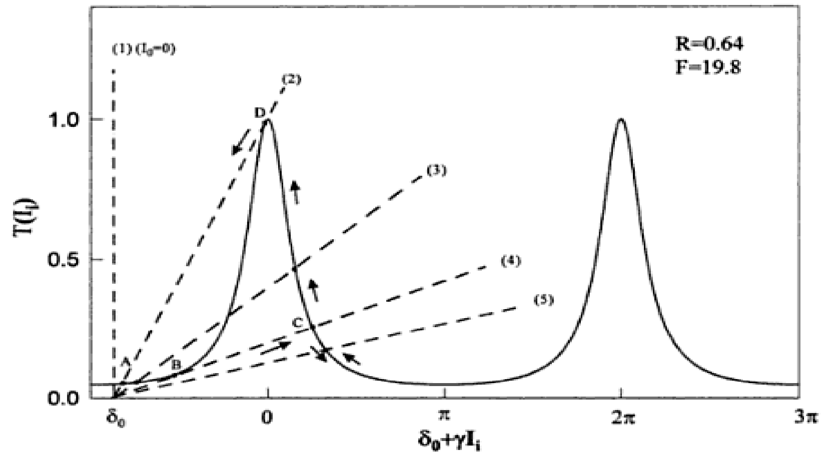



Figure 3.6: graphical solution of equation(3.20)

right hand side of this equation, and the straight lines labeled a through $c$ represent the left hand side for increasing values of the input intensity $I_1$ .We solve Eqn. (3.20) for the internal intensity $I_2$ as a function of the incident intensity $I_1$. This procedure is readily performed graphically by plotting each side of Eq. (3.20) as a function of $I_2$. Such a plot is shown in Fig. 5. 6. We see that the system can possess one, three, five, or more solutions depending on the value of $I_1$[1].

# Chapter 4

# APPLICATIONS OF NONLINEAR OPTICS

The applications of NLO can be divided into two major areas: use as a spectroscopic technique to study physical properties of materials, and the use of NLO functions as the basis for active optical devices. In this review, the second application area is summarized. In this area, the main applications are frequency generation, optical communication, optical switching, optical signal processing, and optical computing.

## 4.1 Frequency generation

Generation of new frequencies by NLO processes has been intensively discussed in the previous sections. The nonlinear processes employed are harmonic generation, frequency mixing and optical parametric oscillation.

## 4.2 Optical communication

In optical transmission systems, NLO effects have been used to cancel the dispersive properties of the nonlinear material and diffraction of light to produce temporal and spatial optical solitons. The propagation of solitons makes it possible to use wavelength division multiplexing (WDM) in the optical transmission system in order to take full advantage of the potential capacity of the fiber. It is also possible to use polarization division multiplexing since solitons maintain a very high degree of polarization over a long distance. The use of optics is advantageous over that of electronics because of the higher carrier frequency used, which gives a potentially higher bandwidth. The realization of optical circuit elements using NLO effects will overcome the limitations of the electronic modulation techniques to exploit the information carrying capacity of optical communication systems.

## 4.3 Optical signal processing

Optical signal processing using combinations of switching elements has two broad categories:

i) in free space optics using parallel beams and arrays of switching elements, and

ii) in guided wave optics using serially connected optical switches.

Much effort has been spent on the experimental study of optical switching and signal processing. An ultracompact (494 Fm long), low loss (0.5 dB/coupler), polarization insensitive, zero-gap directional coupler on InP based on self-imaging through niultimode interference has been reported [19]. 100 MHz digital optical counter using directional coupler switches was built, with which time division multiplexing was also demonstrated [13]. Awave length switching of a picosecond pulse in a quantum well laser and its all optical logic gate operations using stimulated emission have been observed [14]. A nonlinear holographic coupler,[15] logic modules using opto-optical birefringence switching in Bi, SiO, [16] compression of non-amplified femtosecond pulses using a highly nonlinear organic single crystal core fiber in combination with a dispersive delay line of a grating pair a MachZehnder interferometer on switching devices based on optical bistability and multistability [17-21] have been reported.

## 4.4 Optical computing

Electronic computers nowadays use very large scale integration of electronic transistors. Photonics is one among several contenders to replace or at least displace electronics for computing and information processing. The advantages of photonic devices using NLO processes over electronic devices are faster speed, owing to the use of photons instead of electrons, and higher bandwidth capacity. The disadvantages are higher energy requirements and device size limitations related to the wavelength of light. A simple replacement of electronic transistors by optical transistors would not allow us to take advantage of the most important features of photonic devices, such as bandwidth, parallelism and the three-dimensional (3-D) capability of light. The design of new architectures for optical computers is necessary. In addition, the state of the art of photonic materials, i.e. NLO materials, does not satisfy the requirement for parallel switching, and only serial connections can be envisaged. Practically. all optical circuit elements are based on the combination of optical nonlinearity and feedback. The series of devices include optical logic gates, bistable memories, amplifiers (also termed optical transistors or transphasors) and power limiters [22-23]. Requirements for optical computing are as follows: 1) High contrast. A logic device needs to show a large change between logic 0 and logic 1 levels.

2) Steady-state bias. It is necessary to be able to alter optical bias levels controllably in order to make different logic gates.

3) External address. Separate external signal beams can be combined with the holding beam to switch the device.

4) Elements must be cascadable, i.e., the output of one device must be sufficient to switch at least one succeeding device.

5) Fan-out and fan-in. One device drives many succeeding devices using parallel processing. The summed effect of several elements can be readily focused on one device to achieve fan-in.

6) Power and speed. The operating power per device should be of the order of milliwatts or less. For parallel arrays, microsecond switching times will suffice and for serially connected circuits, picoseconds or less are desirable.

All optical switches using resonant NLO interactions in highly nonlinear materials suffer from the problem of overheating, whereas non-resonant, low loss materials have low nonlinearity, requiring long interaction lengths for switching, which is inhibitory for a high degree of integration.

Besides the four areas listed above, examples of applications of nonlinear optics in other areas are laser protection systems for photodetectors and eye [24] using multilayer structures consisting of alternate Kerr type materials and linear materials, optical sensing based on nonlinear phase shifts in the environment (temperature, pressure, specific chemicals, etc.) compared to a standard environment, and pattern recognition.

# Conclusions

▶ In this work we have shown that at large intensities of EMWs one has to take into account the nonlinear terms in the polarization which is directly proportional to $E^2$,$E^3$ and so on.

▶ The nonlinear terms are important if $E$ is the order of inner atomic fields $E = 5 \times 10^9 \frac{V}{cm}$.

▶ These nonlinear terms result:

↪ second harmonic generation,

↪ sum and difference frequency generation, and

↪ optical parametric generation.

ffl We focused on the optically induced bistability (OIB) phenomena, in particular absorptive optical bistability and refractive optical bistability.

▶ Nonlinear optics gives the possibility :

↪to change optical frequencies,

↪ to realize optical communication,

↪ to realize optical signal processing and optical computing.

# REFERENCES


[1] R.W. Boyd, Nonlinear Optics (Academic Press, New york, 1992)

[2] Franken, P. A., Hill, A. E., Peters, C. W., and Weinreich, G., Generation of Optical Harmonics, Phys. Rev. Lett. 7, 118 (1961).

[3] Armstrong, J. A., Bloembergen, N., Ducing, J., and Pershan, P. S., "Interactions Between Light Waves in a Nonlinear Dielectric," Phys. Rev. 127, 1918 (1962).

[4] http://en.wikipedia.org/wiki/Nonlinear optics

[5] M. Kauranen and A. Persoons, J. Mater. Chem., vol. 9, p. 2005, 1999.

[6] T. Tajima and J. M. Dawson, Phys. Rev. Lett., vol. 43, p. 267, 1979.

[7] A. Umstadter, J. K. Kim, and E. Dodd, Phys. Rev. Lett., vol. 76, p. 2073,1996.

[8] C. W. Siders, S. P. Le Blanc, D. Fisher, T. Tajima, M. C. Downer, A.Babine, A. Stephanov, and A. Sergeev, Phys. Rev. Lett., vol. 76, p. 3750,1996.

[9] M. Mlejnek, M. Kolesic, J. V. Moloney, and E. M. Wright, Phys. Rev. Lett., vol. 83, p. 2938, 1999.

[10] J. F, Reintes, in Luser Handbook (Eds: M. Bass, M. L. Stitch), North Holland, Amsterdam 1985.

[11] N. Bloembergen, Y. R. Shen. P l i j n l . Lett. 1964, 12, 504

[12] E. C'. M.Pennings, R. J. Deri. A. Scherer, R. Bhat. T. R. Hayes, N. C.

[13] R. J. Peuerstein, T. Soukup, V. P. Heuring. Opt. Lett. 1991, 16, 1599.

[14] T. Sogawa, Y Arakawa. Appl. Phys. Ltt . 1991, 58, 1709.

[15] J. Chang, S. K. Case, Appl. Opt. 1976, 15, 1800.

[16] L. Liu. X. Liu, Opt. Lett. 1991, 16. 1439.

[17] S. W. James. R. W. Eason, Opt. Lett. 1991. 16, 551.

[18] Y. Ozeki. C L. Tang. App/. Phys. Lett. 1991, 58, 2214.

[19] Y. Tokuda. Y. Abe. K . Kandmoto, N.Tsukada. Appl. Phrx. Lrrr. 1991,5Y.1016.

[20] Kawsguchi, 1. H. White, M. J. Offside. J. E. Carroll. Opr. Lett. 1992,17, 130.

[21] A. W. Snyder. L. Poladian. D. J. Michell, Opt, Lrtr. 1992. V. 17. 118.

[22] S. D . Smith, Nuture, 1985, 316. 319.

[23] A . S r i k e . V. Daneu. J. Goldhar, N. A. Kurnit. Appl. PlzwLrrt. 1969.I S . 376.

[24] K . M. Yoo. R . R . Alf'dno, Opt. Lett. 1991, 16. 1x23.

[25]. D. S. Chemla, D. A. B. Miller, P. W Smith, A. C . Gossard, W. Wiegman.IEEE J. Quuntum Electrun. 1984. QE-20, 265.

[26]. A. Szöke, V. Daneu, J. Goldhar, and N.A. Kurnit, Appl.Phys. Lett. 15, 376 (1969).

[27]. H.M. Gibbs, S.L. McCall, and T.N.C. Venkate-san, Phys. Rev. Lett. 36, 113 (1976).

[28]. K.M. Leung, Phys. Rev. A 33, 2461 (1986).

[29]. N. Kalyaniwalla, J.W. Haus, R. Inguva, and M.H. Birn-boin, Phys. Rev. A 42, 5613 (1990).

[30]. A. K. Kar and B. S. Wherrett, J. Opt. Soc. Am. B 3, 345 (1986).

This project is my original work, has not been presented for a degree in any other University and that all the sources of material used for the project have been dully acknowledged.

**Name: YASABU AYALL**

**Signature:** ______________________

This project has been submitted for examination with my approval as University advisor.

**Name: Prof. Mal'nev V.**

**Signature:** ______________________

Place and time of submission: **Department of Physics**
**Addis Ababa University**
**May, 2013**