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INDUCED ALL OPTICAL BEAM DEFLECTORS FOR ULTRAFAST LOW-LEVEL OPTICAL WAVEFORM DIGITIZATION

P.P. HO
R.R. ALFANO

THE CITY COLLEGE OF THE CITY UNIVERSITY OF NEW YORK
DEPARTMENTS OF ELECTRICAL ENGINEERING AND PHYSICS
NEW YORK, NEW YORK 10031

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Joseph E Brandelik

JOSEPH E. BRANDELIK
Multi-Chip Integration Branch
Aerospace Components Division

Alan J Tewksbury

ALAN J. TEWKSBURY, Chief
Multi-Chip Integration Branch
Aerospace Components Division

Robert T. Kemerley

ROBERT T. KEMERLEY, Chief
Aerospace Components Division
Sensors Directorate

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P.P. HO
R.R. ALFANO

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DEPARTMENTS OF ELECTRICAL ENGINEERING AND PHYSICS
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The feasibility to apply a nonlinear optical based all-optical induced switch for the future ultrafast waveform digitization and processing applications has been tested in this program. Induced optical elements (prism, grating, lens, etc.) can create small scale optical elements for data communication and information processing. The ultrafast all optical deflector is based on a geometric space refractive index change induced by an area-modulated ultrafast laser pulse in a nonlinear optical material. A transient prism-like modulation can be formed and will in turn deflect a signal beam on the picosecond time scale. This program has utilized some of existing facilities, staff, and state-of-the-art equipment in photonic research at CCNY.

A picosecond YAG laser system and a Ti:sapphire femtosecond laser system were used to setup the experiment for the design consideration of a high speed induced deflector and to study promising materials for the induced nonlinear optical process. Nonlinear optical materials included: CS2 liquid, supercooled salol, plastic crystal succinite, ZnSe, glass and doped polymers. They were tested to study parameters such as third order optical nonlinearity, response time, absorption and geometrical distortion. The results using a Bi-Pb-Ga doped glass with fast and large optical nonlinearity are described in section 4.1. Future research should be aimed toward the design of a time resolved DWDM optical interconnect using spectral nonlinear optical elements and the development of a compact system with Terabits/sec to petabits/sec capability using array of transient optical circuits.

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Abstract

There is a need to transmit a large volume of information at high speed for commercial and military applications. The feasibility to apply a nonlinear optical based all-optical induced switch for the future ultrafast waveform digitization and processing applications has been tested in this program. Induced optical elements (prism, grating, lens, etc.) can create small scale optical elements for data communication and information processing. The ultrafast all optical deflector is based on a geometric space refractive index change induced by an area-modulated ultrafast laser pulse in a nonlinear optical material. A transient prism-like modulation can be formed and will in turn deflect a signal beam on the picosecond time scale. This program has utilized some of existing facilities, staff, and state-of-the-art equipment in photonic research at The City College of New York to investigate various technical aspects of the transient beam deflector.

A picosecond YAG laser system and a Ti:sapphire femtosecond laser system were used to setup the experiment for the design consideration of a high speed induced deflector and to study promising materials for the induced nonlinear optical process. Several nonlinear optical materials included: CS_2 liquid, supercooled salol, plastic crystal succinonitrile, ZnSe, glass, and doped polymers have been tested to study parameters, e.g. third order optical nonlinearlity, response time, absorption, and geometrical distortion. The results using a Bi-Pb-Ga doped glass with fast and large optical nonliearity are described in section 4.1. A new phenomenon based on the three-photon absorption process from excited states of ZnSe material has been observed and the result are described in section 4.2. This intensity dependent nonlinear and linear absorption process which changes the pulse shape distribution may be applied to the optical limitor application. Future research should be aimed toward the design of a time resolved dense-wavelength-division-multiplexing (DWDM) optical interconnect using spectral encoded elements and the development of a compact system with tera-bit/second to peta-bits/second capability using an array of transient optical circuits.

1. Summary

Now and in the future, there is a need to transmit a large volume of information at high speed for commercial and military applications. Photonic technology will play an important role. Methods to detect, digitize, and process an ultrafast optical pulse (~picosecond duration) at high repetition rate with high bit accuracy are needed in many military applications. Photonic devices promise rapid switching for uses in computation and communication. In this contract, we have studied the feasibility to apply a nonlinear optical based all-optical induced deflector for the future ultrafast waveform digitization and processing applications. Induced optical elements (prism, grating, lens, etc.) can create small scale optical elements for data communication and information processing. This program was the first phase to create compact optical circuits. The outcome of this program demonstrates the need to follow up with additional research and development effort to build optical circuit devices.

The ultrafast all optical deflector is based on a geometric space refractive index change induced by an area-modulated ultrafast laser pulse in a nonlinear optical material. A transient prism-like modulation can be formed and will in turn deflect a signal beam on the picosecond time scale. Our research program has focused on the studies on the limitation of the optical induced deflector: the materials to be used, the relaxation time, the number of deflection channel, and the minimum power required to induce a deflector. The technology to be developed can significantly advance the signal processing speed with the potential to handle ~ 10^{12} bits/second (tera-bits/sec) upto 10^{15} bits/second (peta-bits/sec).

During the 45 months program period (36 months planned plus 9 months no-cost extension), funds of $150K have been received from Air Force Wright Laboratory. The Center for Advanced Technology of New York State Science & Technology Foundation (CAT) has provided ~ $30K per year to support this research. Additional funds of ~$53K have been matched from CCNY by supporting a post-doctoral research associate and ~ 10% efforts from two faculty members to carry out this program. In addition, two parallel research programs: "Optical transistors" supported by

Ballistic Missile Defense Organization/Air Force Office of Scientific Research (BMDO/AFOSR) and "Nonlinear optical devices" supported by CAT at The City University of New York (CUNY) have provided numerous resources in terms of material fabrication and characterization to support many facets of this research. Funds of $120K from CUNY were secured to purchase a new mode-locked YAG laser system for the use of this research. This program has utilized some of existing facilities, staff, and over six million dollars state-of-the-art equipment in photonic research at CCNY to investigate various technical aspects of the transient beam deflector. Additional support is needed to carry this research to a higher level to produce better and compact induced optical circuits.

In this research program, a picosecond YAG laser system based optical pump system has been setup to initiate the experiment for the design of a high speed induced deflector. and study promising materials for the induced nonlinear optical process. We have measured and evaluated design parameters and performance of nonlinear optical materials for the optical induced beam deflector. These materials included several commercial available materials: CS_2 liquid, supercooled salol, plastic crystal succinonitrile, and ZnSe polycrystallines. Special fabricated materials were used such as: Bi-Pb-Ga doped glass (LBG), and sodium atom doped polymers from Prof. N. Yang of CUNY/CAT. Optical parameters: third order optical nonlinearlity, response time, absorption, and geometrical distortion for the design considerations and limitation of these materials for an induced beam deflector have been studied. The results using LBG glass is described in section 4.1.

Most of the proposed objectives have been achieved. However, there were several drawbacks in this program which were mainly attributed to the failure of the mode-locked YAG laser initially used. It took us about two years to secure additional funds of ~ $30K from CCNY internal sources and to find a competent service person to repair this laser. In the end, in order to obtain a good laser with the necessary beam quality and stability, we had to acquire additional funds of ~ $120K from CCNY to purchase a new laser system to carry out this program. In addition, a femtosecond Ti:sapphire laser system with amplifier has also been applied to measure the nonlinear time response for ultra-high speed signal processing applications. Using a CS_2 liquid as the induced deflecting material, ~ 10 channels of deflection points have been obtained at the 40-ps time scale.

Due to heating effect from multi-photon absorption process which is slow and large in optical nonlinearity, the fast transient nonlinear induced optical beam deflector using CS_2 or other NLO elements may be limited for the high repetition frequency operation. Larger band gap uv NLO materials are needed such as GaAlN alloys. A new phenomenon based on the three-photon absorption process from excited states of ZnSe material has been observed and the result are described in section 4.2. This intensity dependent nonlinear and linear absorption process which changes the pulse shape distribution may be applied to the optical limitor[1] application.

With the improvement of ultrafast laser sources and the direct need by optical communication field for novel photonic applications, future directions of this research should be aimed toward the development of a compact system with tera-bits to peta-bits capability to be adapted in real-world compact circuit applications and the application toward the design of a time resolved DWDM optical interconnect[2] using spectral nonlinear optical elements. This program needs to be advanced further with additional funding to bring optical induced circuits to the next level of usage.

2. Introduction

Light can be used to control and modulate light using nonlinear optical (NLO) effects. The next generation high speed communication and computation devices will use NLO to handle tera-bits/sec signal processing[3-7]. Optical processing can be used to digitize electromagnetic waveforms from microwave to optical regimes. Based on the fast switching, parallel and free-space interconnect[6,7], basic research has already been performed to implement various types of optical intensity-, phase-, and polarization-encoded switching schemes for computing and processing data. Optical Pockel and Kerr effects have been suggested for an ultrafast optical wave-mixing by which the spatially modulated optical pulses interact in nonlinear materials to produce a logic output[4,8,9] with picosecond to femtosecond logic operations. To keep up this logic gating speed, an ultrafast optical spatial encoding or modulating scheme to digitize a wavefront on picosecond/femtosecond scales should be incorporated and developed. Future bandwidth requirements from Web, on line virtual reality, and 3D holography will require peta-bits per second using all optical switching.

Various optical analog to digital conversion (A/D) approaches have been studied over the years. For the Cross-phase-modulation (XPM)[10] A/D, the main problem is the requirement of high power input optical signals. For the spatial light modulator (SLM), the main limitation in the development is the control of optical beam on the fast time scale for a relative small scale dimension. Using an electro-optic effect with a liquid crystal or a photo-refractive crystal is slow ($\sim 10^{-3}$ s). Optical SLM are commercially available[11,12]. For an intensity-encoded optical signal processing and computing, SLM scheme offers a 2D flexibility. This type of SLM is not suitable for other encoding schemes, such as an angular-coding which has applications in A/D, multi-port interconnect, multi-valued logic, and other optical scanning and deflection operations. The proposed program will extend our previous results to investigate virtual induced optical devices to develop deflectors for the digitization on weak optical waveforms, e.g. single shot evens with ~10-ps resolution.

There are several optical beam deflection schemes. Beside the slow speed mechanically tuned mirror deflector, both the electro-optic and the acousto-optic beam deflectors are available[13,14]. Using various state-of-the-art integrated optics methods, a 100 MHz deflection speed has been achieved. To further increase the speed, the material-capacitance to voltage needs to be minimized which implies the size of the device needs to be further reduced. Although the further size reduction is not impossible, this approach is difficult. An alternative way to increase the deflection is to use an all-optical process using nonlinear optical materials. It has been shown that using an optical induced dynamic grating, an induced diffraction can serve as a beam deflection device. Two coherent optical pulses interfere inside a nonlinear material, the interference fringe modulates the refractive index of the medium to form an induced grating. When the third optical probe pulse arrives, this probe beam will be diffracted to an off-axis direction. The diffraction-based deflection method has been used to study material relaxation processes and other properties in picosecond time domain[15]. However, for a device application, such an approach suffers from two drawbacks: the high device complexity and the low deflection efficiency. The deflected beam energy from the first order diffraction is too weak in comparison to the un-deflected zeroth order beam. The optical deflection method uses an induced optical prism approach. A design of a 1-D beam deflector has a potential of ~ 100% diffraction efficiency. A signal beam along the z-axis from a laser is sending through a nonlinear optical material pumped by an induced prism in x-direction. Depending on the induced spatial modulations, the transmitted beam can be spatially modulated and deflected into different directions. Using a charge-coupled-device (CCD) camera, the locations of the modulated deflection beams can be determined.

In our research program, we have performed key experiments to quantitatively determine key optical and temporal properties of optical beam deflectors, such as: the deflection angle, repeatability, and resolution of induced beam defection; and operation parameters, such as: tested induced beam deflector with different organic liquids, polymers, and doped glasses; tested induced deflectors using slow and high speed deflection schemes; and evaluated design specifications of optical components.

3. Methods, Assumptions, and Procedures

3.1 Methods The basic method of the transient beam deflector and switch was published[16] in Optics Letters in 1991 and a patent was awarded[17] to CUNY (US#5,126,874) in 1992. One-dimensional experimental results fit the theoretical predictions. There were other optical induced elements proposed in the patent, such as lens, grating, etc., which have not been studied so far to create an optical circuit. An induced all-optical deflector as shown in Fig.1 consists of four key elements: third order nonlinear optical material (NOM), pump beam, signal beam, and spatial mask. The optical induced deflector operates as follows: The pump and signal beams enter and overlap inside the NOM in perpendicular directions. Both signal and pump beams are assumed to be plane waves. The pump beam is area-modulated before entering the NOM. The spatial mask is a triangle to create an induced prism in NOM. The induced refractive index change inside NOM is:

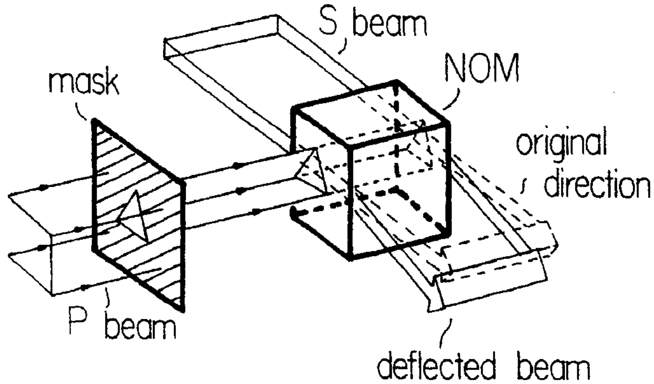


Fig.1 Schematic of an induced area-modulated all-optical-deflector. A triangular area modulation is used.

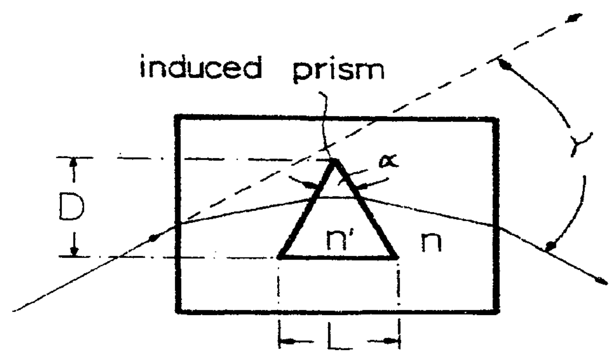


Fig.2 Optical ray-tracing geometry of the induced deflector. n' and n are the material refractive indices with and without the optical modulation. α, D, and L are the apex angle, the aperture, and the base length of the isosceles triangle set by area modulation; γ is the deflection angle.

$$\Delta n = n' - n = n_2 I(t,r) \quad , \qquad (1)$$

where n', n, n_2 denote the material refractive index with, without the presence of the pump beam, and the nonlinear refractive index coefficient, respectively, and I(t,r) is the intensity of the pump pulse in time and space. The induced refractive index change causes an induced transient prism within the modulated triangle spatial mask. In this manner, when the signal beam passes through the induced prism at the same time, it will undergo a direction change: an induced transient deflection occurs for the weak signal beam. This approach has the potential for high speed switching and virtual optical elements.

For the induced beam deflection, consider the geometry for an isosceles prism shown in Fig.2. The apex angle of the isosceles triangle is α and the deflection angle is γ. Similar to eq.1, the refractive indices of the modulated and unmodulated area are n' and n, respectively. Following the Snell's law, n'/n can be written as:

$$n'/n = \sin[\alpha/2 + \sin^{-1}(\sin\gamma/2n)]/\sin\alpha/2 \quad . \tag{2}$$

For small deflection angle, $\sin\gamma \sim \gamma$. In a first-order approximation, eq.2 can be simplified and the deflection angle is given by

$$\gamma \sim L\ \Delta n/D \quad , \tag{3}$$

where L and D are the base and height of the induced prism, respectively.
For an probe beam with Gaussian spatial profile, its far field direction angle is

$$\gamma(\text{beam}) = \lambda/\pi w_o \quad , \tag{4}$$

where λ and w_o are the wavelength and spot size of the signal beam, respectively. By comparing eqs. 3 and 4, there are N possible resolvable channels in the far field as,

$$N = \gamma/\gamma(\text{beam}) = \pi L\ \Delta n\ w_o/(D\lambda) \quad . \tag{5}$$

For instance, let $L/D = 4$, $w_o = 2$-mm, and $\lambda = 530$-nm, $N = 4.5x10^4 \Delta n$ is obtained from eq.5. Since it is possible to obtain the induced index refraction change Δn around the order of 10^{-3} from laser pulses with various duration in semiconductors, polymers, doped glasses, and liquid-crystals, all optical deflectors with different speed and different resolvable deflection angle can be implemented as a fast A/D device. With a multiple time-axes deflection approach, the total number of pixel points can be as high as N_x x $N_y \sim 45x45 \sim 2025$. More than 2000 optical ultrafast A/D sampling resolutions can be realized. The bit accuracy of this A/D method which depends on the known technology of CCD camera processing is > 10 bits. Once the signal has been deflected and recorded by CCD, the processing speed can be slower and depends on the number of multiple computation processors. The key of the high speed digitization is the high speed induced optical deflector.

Our results of an induced prism using CS_2 nonlinear medium is shown in figures 3 and 4. The optical nonlinearity x^3 of the CS_2 is $\sim 10^{-12}$ esu with a ~ 2-ps response time. The beam deflection angle of a 530-nm laser pulse through a CS_2 nonlinear material pumped by a 1060-nm laser pulse has been demonstrated. The output signal pulses with and without deflection recorded by the optical multi-channel analyzer are compared. The measured transient beam deflection angles are plotted as a function of the pump intensity of the 1060-nm laser pulse and probe delay time in figures 3 and 4, respectively. Good linearity between the pump beam to the deflected angle has been obtained up to 10-mRad.

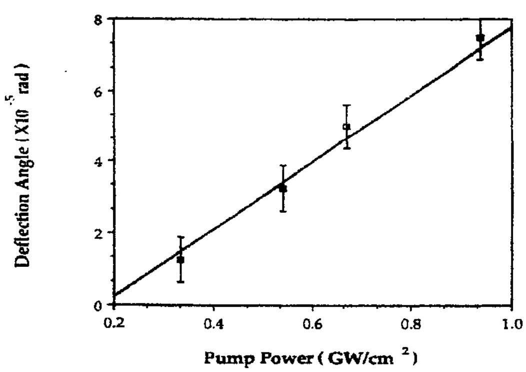


Fig.3. Intensity dependence of deflection angle. The solid line is the linear fit of experimental data

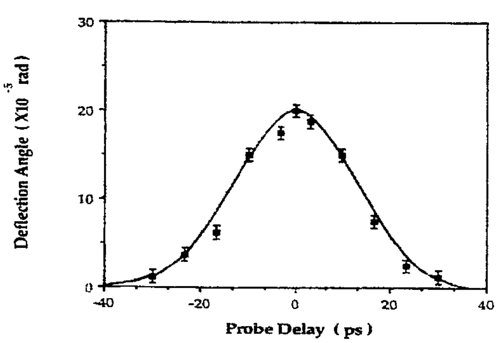


Fig.4. Deflection angle versus the delay time between the pump and probe signal beams. The solid curve is a Gaussian fit.

3.2 Assumptions

Assumptions of this research involves two key parameters: optical nonlinearity (n_2) and response time of the material used for the induced beam deflector. Our preliminary studies indicate that an induced refractive index change of $n_2I > 10^{-4}$ is needed to achieve a ~ 10 bit (1000:1) digitization accuracy. The larger the n_2, the smaller the required pump energy is. Using a CS_2 sample, the pump pulse energy is ~ 10-mJ. Optical materials with larger nonlinearity, e.g. polymers, liquid crystals, and organic compounds will be tested in this program. A linear sweep of the induced refractive index change is desired for the ultrafast waveform digitization. No existing method can provide a perfect linear time sweep. The time sweep linearity has to be measured, calibrated, and normalized. Research is needed to obtain optimum NLO materials.

3.3 Procedures

Laser Sources Two laser systems with different pulse duration, energy, and repetition rate were used in this program to generate laser pulses to test digitization optical circuits for the best combination of the design parameters. The Ti-sapphire fs laser system provides the fastest possible pulse for optical signal processing. These laser systems are listed below:

Laser Systems	duration	pulse energy	repetition rate
Ti-sapphire fs laser system	100-fs	10-uJ	200-KHz
Mode-Locked YAG Laser	30-ps	100-mJ	10-Hz

Nonlinear Optical Materials A number of nonlinear optical materials were tested for the material of the induced prism. An induced refractive index change of $\Delta n = n_2I \sim 10^{-5}$ to 10^{-4} is needed to separate the deflected beam from the signal beam. The use of a focused picosecond YAG laser pulse into a CS_2 cell can satisfy this material nonlinearity requirement with time resolution of ~10-ps. Certain organic materials and lead glass have large and fast nonlinearity[18]. New photonic materials with larger nonlinearity are needed to cover the fast and slow time response. Additional studies on NLO materials without active multi-photon effect are needed.

Sweeped Wavefront Generation The temporal/spatial resolution of the measurement depends on the ratio of the deflected angle and the far field diffraction of the beam to be measured. The collimation of the beam to be measured is important to the digitization. The pivot of this method depends on the induced deflection of the beam to be measured, which converts the temporal signal to spatial signal. To obtain a linear temporal to spatial conversion, a linear index change in time is essential. For the materials with nonlinear response much faster than the pulse duration of the pump pulse, the induced index change is transient. The temporal property of the induced index change has the same temporal function as the pulse shape itself. A sawtooth or a triangle optical pulse is an ideal pump pulse wavefront to induce a linear index change in time. For materials with nonlinear response much slower than the pulse duration of the pump pulse, the temporal distribution of the index change is the convolution of the temporal pulse shape with the temporal response function of the nonlinear material. The nonlinear temporal response function of the material is needed to find out what type of pump pulses are ideal to generate linear index change in time. When Δn changes linearly as a function of the time, the deflected angle of the output signal through this induced deflector will also change linearly in time. In this manner, the temporal profile of the incident optical signal will be dispersed linearly into different spatial location as a function of angle (linearly proportional to time).

To extend the overall signal time for the digital conversion using a single optical pulse using approximately the generation of the linear index change in time, an alternate method will use an etalon to generate a quasi-sawtooth optical pulse. An etalon consists of a pair of mirrors. By passing an optical pulse through an etalon of known spacing d, a series of exponentially decaying intensity pulses will emerge. The time separation between nearest two pulses is $\blacktriangle t=2d/c$, where c is the velocity of light. The intensity profile of the emerging train is a decaying exponential with each subsequent peak reduced by $(1-T)^2$, where T is the coated transmission coefficients of the mirrors. For each round trip of the pulse between the mirrors, a light pulse (K) of intensity $I_K = I_0(1-T)2K$ is produced, where K = 0, 1, 2 ,3, ... n. Since $I_K/I_{K+1} = 1/(1-T)^2$ = constant, the envelope formed by the peaks of the pulses follows a single exponential decay in time as $I = I_0 \exp[-\blacktriangle t/\ln(1-T)^2]$. By adjusting the transmission coefficient T and the spacing between the two mirrors d, a quasi-saw optical pulse can be obtained.

4. Results and Discussion

The program has successfully repeated and demonstrated the experiment of an ultrafast induced beam deflector using a CS_2 liquid nonlinear material pumped with a 30-ps laser pulse. Nonlinear optical materials: organic liquids, polymers, supercooled liquids, semiconducting materials, and special fabricated glasses have been measured for the induced deflection with the response time from sub-picoseconds to nanosecond regimes. Two major accomplishments in this program: nonlinear optical properties of heavy-element-doped glasses (LBG), and nonlinear optical processes in ZnSe are summarized below.

4.1 Femtosecond Optical Kerr Switch Using Lead-Bismuth-Gallium Doped Glass (LBG)

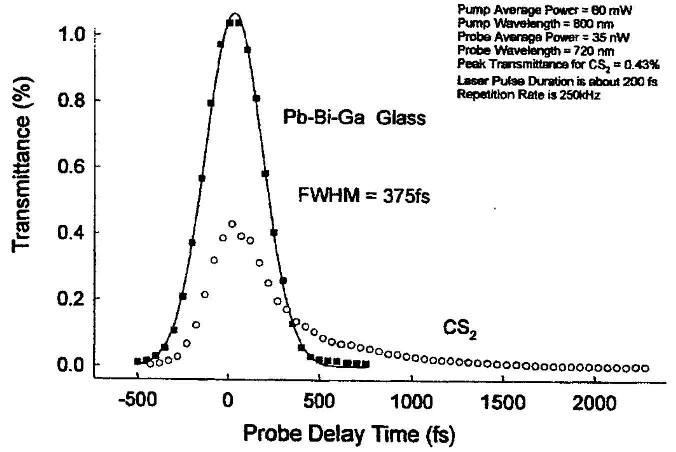
Photonic devices such as optical gates and logic circuits circuits using nonlinear optical (NLO) processes based on the third order susceptibility coefficients ($\chi 3$) promise the ultimate switching speed for uses in optical computation and communication fields.

Optical Kerr gate[18] (OKG) has been used as an ultrafast gate for time-resolved biomedical optical imaging and optical interconnect applications. Ultrafast photonic device applications like the induced optical beam deflector, optical analog to digital converters, and optical transistor amplifiers require χ^3 materials with fs response time and large Kerr coefficients. For most commonly known NLO materials in the visible and near infrared regimes, their non-resonant χ^3 values are in the range of $\sim 10^{-14}$ esu (silica glass, fs response time) to $\sim 10^{-12}$ esu (CS_2, $\sim$ 2-ps response time). Several semiconducting, organic or polymeric materials seem to have very large χ^3 values[18,19]. However, these materials are limited by either being too thin, consisting of diluted nonlinear active molecules in a host medium, or having a slow response time. After taking these factors in account, such as the sample thickness (z), concentration (n), and response time (τ), the effective induced nonlinear refraction change ($\sim \chi^3 nz/\tau$) from the CS_2 liquid is still the best known NLO material in the ps time regime. Multi-photon processes limit the use of CS_2 and other materials for higher repetition rate. For many ultrafast applications, new nonlinear materials with a larger Kerr constant with ps/fs response time are needed.

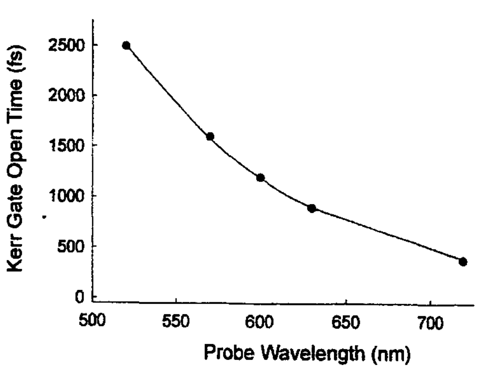
Among the potential NLO materials, glasses have the advantages of easy fabrication, high transparency, high chemical and thermal durability, and high optical damage resistance. Glass is the basic building material for optical communication and other photonic devices. Glasses can be considered random networks of covalent and ionic bonds with short-range-order is preserved. Recently, several research groups[19] have demonstrated that the nonlinear refractive indices of oxide glasses can be increased by addition of heavy-metal cations, such as Pb, Bi, and Tl. The nonlinear refractive indices of these glasses were measured using Z-scan, four-wave mixing, and third-harmonic generation. The response time and dispersion of the optical Kerr gate from a heavy element doped lead-bismuth-galliate $Pb0\text{-}Bi_20_3\text{-}Ga_20_3$ (**LBG**) glass have been determined using high repetition rate fs laser pulses. The χ^3 value of this glass gated at 800-nm and probed with a supercontinuum source in the non-resonant region was $\sim 10^{-11}$ esu with < 200-fs time response.

A laser pulse train with 200-fs pulse duration at 800nm operating at 250kHz was obtained from a regenerated amplified Ti:sapphire laser system. The output beam of the laser was split into two parts, one beam was used as the gating beam and the other was used as the probe beam. The gate pulses induce transient birefringence in the nonlinear glass and cause the polarization change of the probe light. The desired wavelength of the probe beam was extracted from the supercontinuum using a narrow-band filter with a 10-nm spectral transmission width. The time delay between gating and probe pulses was controlled by a stepping-motor with a minimum temporal resolution to be ~ 6.67 fs. Heavy-metal oxide LBG glasses were fabricated by melting mixtures of Pb_3O_4, Bi_2O_3 and Ga_2O_3 at 900°C in a gold crucible in air from either in house or supplied by Corning Inc. The composition of the LBG glass was ~ $40\%PbO\text{-}35\%BiO_{1.5}\text{-}25\%GaO_{1.5.}$ The sample was cut to a 1-mm thick plate and polished for optical measurements. The absorption spectrum of the glass exhibited good transparency in the spectrum range > 600-nm and the absorption edge was at ~ 480-nm.

In figure 5, the measured time-resolved transmission signals of the OKG using the **LBG** glass gate is displayed as the solid squares. The gating pulse wavelength was at 800-nm and the probing pulse wavelength was at 720-nm. For the comparison purpose, a standard CS_2 OKG gate measurement is also displayed as the open circles in figure 5. The liquid CS_2 was situated in a 1-mm thick cell. Both samples were measured under the same gating and probe power condition. The salient feature of this figure indicates that the temporal profile from the glass OKG was symmetrical with the full- width at half-maximum (FWHM) of ~ 350-fs while the CS_2 gate has an



asymmetrical decay tail. This ~ 1-ps decay time is mainly attribute to the reorientational relaxation process from the CS_2 molecule. The peak transmission efficiency from the glass OKG raw data was ~ 2.35 times larger than that from a CS_2 gate. In addition, the measured gate opening times of the time-resolved OKG transmission signal for different probing wavelengths from 720-nm to 520-nm are displayed in figure 6. When the probing wavelength was shorter, besides the time delay of the peak transmitted signal due to the normal dispersion of the supercontinuum generation, the gated FWHM time was also found to be increased from 350-fs to 2.5-ps. The increasing of the gating width is attributed to the dispersion of the supercontinuum generation medium.



To compare the absolute value of the Kerr nonlinearity n_2 of the LBG glass used in the OKG with a standard CS_2 OKG, an empirical equation was used under the same experimental condition. The transmission T of the probe light through an OKG is determined by the gating pulse intensity I_g, optical Kerr coefficient n_2 , and the sample length L. When the probe peak transmission T is small (< 10%), the following approximated relationship can be obtained as ~ $[n_2 \, L \, I_g]^2$. Using the measurement of the peak transmitted signal at the zero delay time displayed in fig.5 and considering the surface reflection loss from the gating sample due to the different linear refractive index [n (glass) ~ 2.3 , n(CS_2) ~ 1.6] from both the gating beam (800-nm) and the probing beam (720-nm), n_2 (glass)/n_2(CS_2) ~1.9 was obtained. The transient OKG signal from an LBG glass gated at 800-nm was found to be fast beyond the 200-fs pulse resolution and the absolute transmitted signal was > 2 times larger than that from a CS_2 gate. It is believed that this fast nonlinear response should be of electronic origin and < 10 fs. Heavy metal doped LBG type glasses are good candidates for applications using femtosecond Kerr shutter and all-optical deflector.

4.2 ZnSe Temporal Laser Pulse Shaping

ZnSe has excellent physical, chemical and nonlinear optical properties as well as low absorption spanning from the red to infrared. The temporal behavior of a 40-ps laser pulse propagation through a ZnSe plate was observed using a single shot optical Kerr gate (SOKG)[21]. Shaping and shortening of a laser pulse were found to be intensity dependent. A mode-locked Nd:YAG laser was used to generate 1064-nm and 532-nm pulses of 40-ps and 30-ps, respectively. The 30 ps 532-nm probe pulse was passed onto a ~ 90° blazed reflection grating to be transformed into a ~45° oblique temporal front covering over 200ps temporal window. A lens was used to focus the probe beam into a 1-cm long CS_2 Kerr cell to form an extended probing time base. Another lens collected the transmitted beam onto a CCD camera for analysis. The channel/pixel number of the CCD camera displayed the time. In this manner, ~ 1,000 time divided signals can be displayed for a single probing pulse to accurately monitor the temporal profile of the 1064nm pulse. This SOKG approach can measure the shape of a laser pulse (FWHM ~ 40-ps) with about 8-ps temporal resolution over a 200-ps time window. Pulse profile measurements through a ZnSe were performed to determine the pulse reshaping arising from nonlinear intensity dependent processes.

Measured SOKG temporal profiles of the transmitted 1064-nm pulse through a 3-mm thick ZnSe plate at the intensities of incident pulses of a) 0.365GW/cm^2, b) 1.46GW/cm^2 and c) 3.65GW/cm^2, are displayed in figure 7. When the incident intensity increased, the output pulse shortened and the trailing portion was reduced. At I ~ 3.65GW/cm^2, most of tail disappeared. A 3-mm glass plate under the same conditions was used as reference. These results are shown in the upper left insert of figure 7. The temporal profiles from a glass sample are nearly the same. According to the intensity temporal profile measurements, there appears to be a critical value at ~ 1.5GW/cm^2. When the intensity of 1064-nm laser pulse was below this value, the magnitude of signal changed. This change can be seen as curve a, curve b, and curve c in figure 7. When the incident intensities were below 1.5GW/cm^2 from the curve 7a and 7b, the normalized intensity profile shapes were almost identical. When the intensity of 1064-nm laser pulse was above this value, a large reshaping and shortening occurred as shown in curve 7c. The peak shift and the width reduction between curve 7b to curve 7c were ~ 15-ps and ~13-ps, respectively. In addition, the tail portion was significantly reduced in curve 7c.

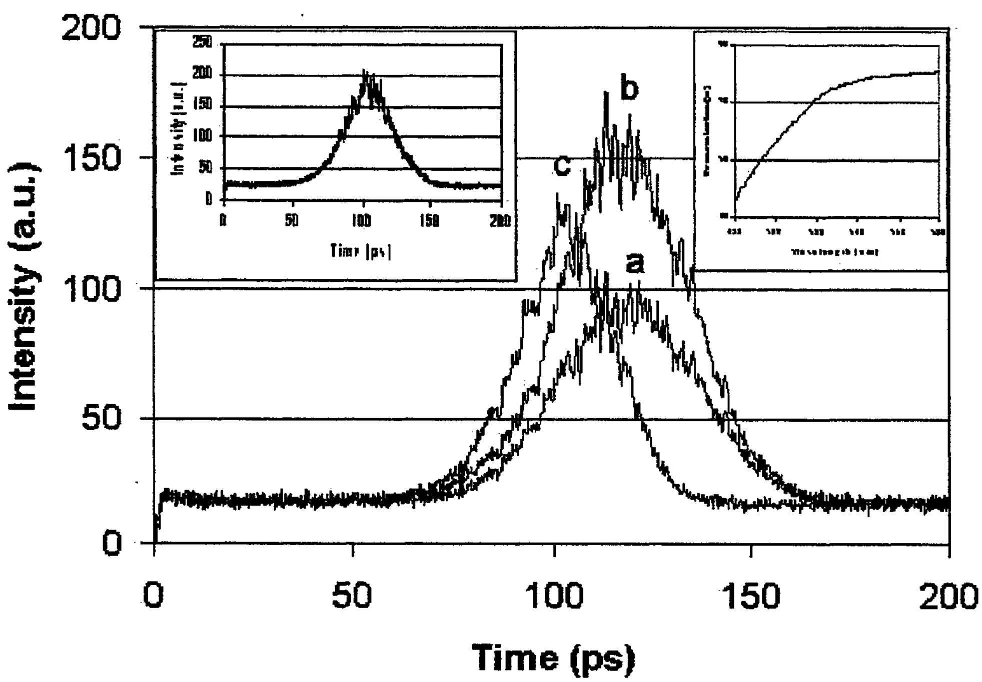


Fig.7 SOKG temporal profiles of a 40-ps 1064-nm laser pulse propagating through a 3-mm thick ZnSe plate with the incident laser intensity at (a) 0.365 GW/cm^2 (b) 1.46 GW/cm^2 (c) 3.65 GW/cm^2. [insert left] Temporal profiles of a 40-ps 1064-nm pulse of three different intensities through a 3-mm thick glass plate located at the same position as the ZnSe. [insert right] Transmission spectrum of a 3-mm thick ZnSe plate.

The observed shaping and shortening is different from changes that should occur for a conventional saturable absorber (single-photon absorption). The absorption in a saturable absorber mostly occurred in the leading edge of the propagating pulse while the absorption shown in this work mainly occurs in the tailing edge of the propagating pulse. The transmitivity of the 1064-nm pulse through a ZnSe decreased when its incident intensity was increased, by contrast the transmitivity of a laser pulse through a saturable absorber could increase when the incident intensity increases. The salient features of curve 7c are pulse profile shaping and shortening. These changes are different from the observation made in CS_2, which are caused by the mutiphoton absorption and Kerr nonlinearity.[21]

The observation of a pulse propagating through a ZnSe can be attributed to the two-step absorption processes where two-photon absorption excites carriers to mid-gap states followed by linear absorption to higher conductor band states, as well as negative nonlinear dispersion. Since the band gap-energy of a pure ZnSe crystal is ~ 2.68 eV (λ=460-nm), there should be no two-photon absorption (TPA) of 1064-nm pulses but three photon absorption.[22] The ZnSe sample used in this measurement was a commercial amorphous window plate. Its band-gap energy is ~ 2.63 eV (λ=468nm). Single-photon absorption at 532-nm is arising from gap states. These states appears to be available for possible TPA at 1064-nm. The two-step absorption, nonlinear refractive index and nonlinear dispersion can modify the profile of 1064-nm laser pulse. The two-step absorption results in a larger reduction in the trailing part of pulse than that in the leading part.[23] The nonlinear refractive index and dispersion can result in the self-focusing and self-steepening of the laser pulse. When the incident laser intensity is below a certain critical value, two step absorption and the nonlinear dispersion are small and the pulse distortion is small. The change of measured 1064-nm pulse profiles shown in curves 7a and 7b can be accounted for by nonlinear self-focusing process in ZnSe. Self focusing can also produce the critical onset observed. When the incident laser intensity is above the critical value, the trailing part reduction shown in curve 7c can arise from two-step absorption and the leading edge self-steepening due to negative nonlinear dispersion.

5. Conclusion and Future Directions

Most recently, the commercial market of optical communication and networking technology have grown exponentially. All optical network and switches will become a necessity for ultra-high speed information transfer in future industry, military, academy, and home usage. The outcome of our all-optical induced deflector program has laid a solid foundation in the understanding of some of the key properties in physics and materials needs for upcoming tera-bits/second optical switching and networking technology.

A new class of nonlinear optical material, LBG glass, has been investigated with femtosecond response time, large nonlinearity, and good optical quality as a potential candidate to serve the optical networking in the new era. Intense ultrashort laser pulses propagating through a "transparent" nonlinear optical material, such as a ZnSe plate or a long silica optical fiber, may all experience multi-photon absorption process which can change the intensity and pulse shape of the signal to affect the speed and amplitude of modulated pulse train. These phenomena will become issues for high speed networking and detection considerations.

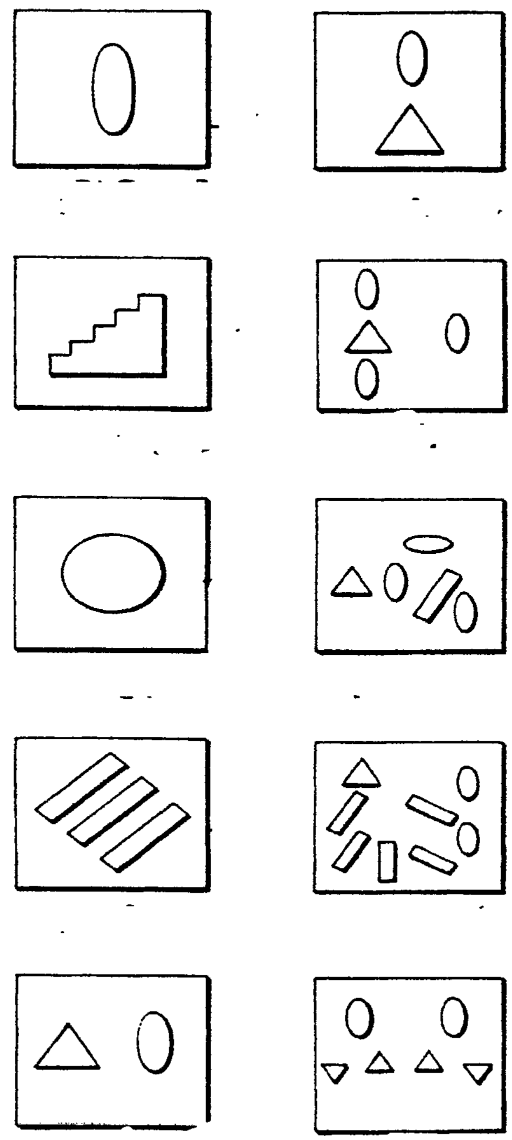


Fig.8. Examples of induced optical elements for optical circuits

Our research has revealed new physics and material considerations such as multi-photon effects for the high speed and high volume communication and computation applications. Additional research is needed to explore these new discoveries and research of better NLO materials for future real world photonic applications in high speed and wideband information transmission and processing at peta-bits/sec. Future research directions needs to explore new materials, compact and low power consumption devices such as induced optical elements: lens, beam splitter, and grating, (see figure 8) based on new NLO materials, processes, and multi-optical elements to create optical circuits to switch and process tera-bits to peta-bits/second information.

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