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Nonlinear optics and its applications in frequency multiplication and imaging

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ABSTRACT
In linear materials, the response is always proportional to the stimulus. The induced polarization is proportional to the field and the susceptibility is independent of the field. However at high fields, the polarization is proportional to the field and hence the susceptibility starts depending on the field. It is called Nonlinear Optics (NLO). Nonlinear optics is the study of the phenomena that occur as a consequence of the modification of the optical properties of a material system by the presence of light. It deals with the interactions of applied electromagnetic fields in various materials to generate new electromagnetic field altered in phase, frequency, amplitude or other physical properties. Nonlinear optics is gaining attention due to its wide application in the area of laser technology, optical communication, data storage technology, optoelectronic, electro-optic, photonic, semiconductors, ferroelectric and superconductors devices. The scope of the paper is to investigate various applications of the non linear optics.

KEYWORDS- Nonlinear optics, NLO, nlo application, SHG, frequency doubling, nlo sensors

I. INTRODUCTION

Before the advent of the lasers, it was assumed that optical parameters of the medium are independent of the intensity of the light. The reason is that, the electric field strength generated by the non-laser light sources (is of the order of 10^3 V/cm), is very much smaller than the inter-atomic fields i.e. 10^7 to 10^{10} V/cm of the medium. Due to the fact that the non-laser light sources are unable to affect the atomic fields of the medium and there by the optical properties of the medium are independent of the intensity of the light. Lasers [1,2] have drastically changed the situation as they generate electric field strength varying from 10^5 to 10^9 V/cm, which in turn helps to estimate the non-linear optical properties of the medium

Nonlinear optics is completely, a new effect in which light of one wavelength is transformed to light of another wavelength [3-5]. The creation of light of new wavelength can be well understood, as we think about the electrons in nonlinear crystal. Electrons in a nonlinear crystal are bound in potential well, which acts like a spring, holding the electrons to lattice point in the crystal. If an external force pulls an electron away from its equilibrium position the spring pulls it back with a force proportional to the displacement. The spring's restoring force increases linearly with the electron displacement from its equilibrium position. The electric field in a light wave passing through the crystal exerts a force on the electrons and pulls them away from their equilibrium position. In an ordinary optical material, the electrons oscillate about their equilibrium position at the frequency of this electronic field [6]. According to the fundamental law of physics, an oscillation charge will radiate at its frequency of oscillation, hence these electrons in the crystal "generate" light at the frequency of the incident light wave.

APPLICATIONS OF NONLINEAR OPTICS

In the diversifying laser and light applications, most of the nonlinearities resulted from light interacting virtually with the material. In this area, the main applications are frequency generation, optical communication, optical switching, optical signal processing and optical computing [7-9]. The second set considers applications where the light changes the material through which it passes, either permanently or rapidly. These applications are labeled as: machining (where material is changed permanently), spectroscopy (where atoms and molecules are changed temporarily) and analysis tools (where selective species are changed). Applications of NLO in information technology can be realized in our day to day activities like data storage, sensor development, etc. The applications of NLO can be divided into three major categories: use of NLO functions as the basis for active optical

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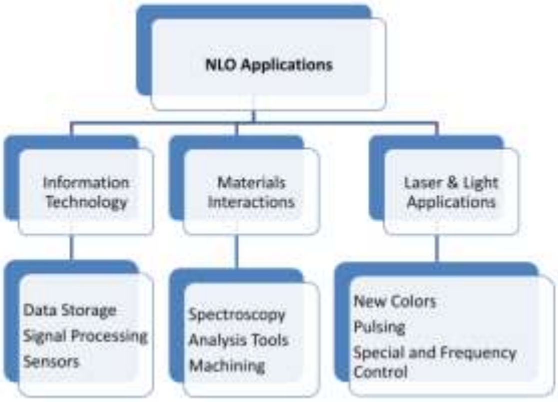
devices, the use as a spectroscopic technique to study physical properties of materials and the information technology. [10, 11]



FREQUENCY CONVERSION

Devices in this category will be utilized mainly for second harmonic conversion of coherent laser radiation. There are two main wavelength regions and laser power regimes of interest. The first category applications is the conversion of low or moderate power diode laser light sources from 830 nm region to the 415 nm region. The driving force of this application is the improvement of packing density in the optical memories, associated with improvements in focusing shorter wavelength. This is because the limit of the resolution of the lens which is directly proportional to the wavelength of light and hence in principle, four fold amount of information can be stored or detected from the memory. The second type of applications includes frequency doubling and mixing of high power laser light sources [12-14].

Second harmonic generation (SHG; also called frequency doubling) is a nonlinear optical process, in which photons interacting with a nonlinear material are effectively "combined" to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons. It is a special case of sum frequency generation.

OPTICAL POWER LIMITING

Optical power limiters are the nonlinear optical materials, which can lead to reduced transmittance when exposed to intense optical radiations. Optical limiting can be used for pulse shaping and pulse compression, but its main applications are sensor and eye protection against the high intensity lasers [15]. Photonic sensors, including the human eye, have a threshold intensity above which they can be damaged. By using the suitable optical limiters, one can extend the dynamical range of the sensors, making them to function at higher incident intensities. An optical limiter, in order to use it in practical applications, should have low input threshold, wide dynamic range, fast optical response (<10 μs), broadband response, high linear transmittance, low optical scattering and good mechanical, thermal and chemical stability. An ideal optical limiter is perfectly transparent at light intensities below a threshold level, and above this level the transmitted intensity gets clamped at a constant value [16]. The output energy transmittance versus input intensity for an ideal optical limiter is shown in Figure.

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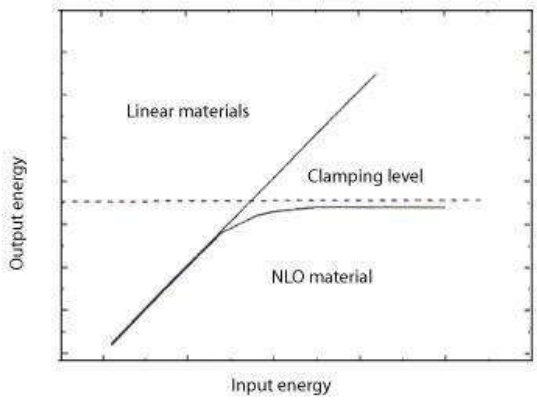

Figure: Schematic diagram represents the optical limiting behaviour of the linear and nonlinear optical materials

HARMONIC GENERATION

Second harmonic generation (SHG) of the Nd:YAG laser (wavelength = 1.06 µm) and its solid-state laser cousins have been the most efficient source of coherent green light (wavelength = 532 nm) for a number of years. The ubiquitous green laser pointer is the culmination of applying NLO to efficiently turn invisible Nd:YAG output into highly visible green. The NLO crystal KTP is the largest active component in the green laser pointer because all optical nonlinearities are weak. Even so, harmonic generation is a lossless process and diode-pumped solid state lasers (DPSS) can be very efficient [17]. When the nonlinear crystal is placed inside the laser cavity, the efficiency of second harmonic can approach 80%. The larger optical fields of picosecond (ps) or femtosecond (fs) pulses can generate second harmonic even outside the cavity with efficiencies approaching 100%.

Efficient generation of short-wavelength coherent light opens up a wide variety of photo-chemical reactions that are valuable because they proceed differently than thermal reactions. Photocatalysis, photodissociation, photoelectrolysis, photosynthesis, photo-polymerization, photoresist (for lithography), are all processes that require short-wavelength light. These processes use SHG of Nd-based lasers for localized processing and/or specialized excitation with ps pulses. While these processes may not directly require NLO, they do require short wavelengths that are often fulfilled most conveniently by SHG.

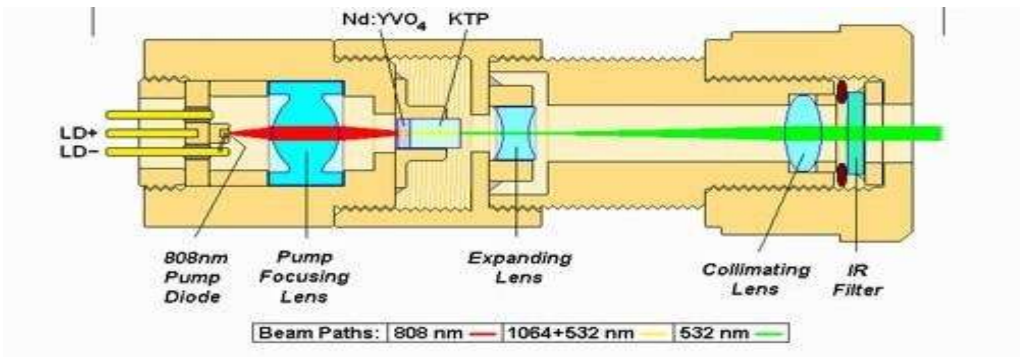

Fig. Diagram of a green Diode-pumped solid state laser pointer.

STIMULATED RAMAN LASERS

Stimulated Raman scattering (SRS) offers gain at frequencies separated from the laser pump by a molecular vibration. The variety of laser pump wavelengths and SRS materials provides exceptional diversity for lasers. The most impor tant application is Raman lasers and amplifiers in fibers for telecommunications. In general, bulk Raman lasers require high-power pulsed laser pumps and provide an output at longer wavelengths. Geometries may be single pass amplifiers, resonators (Raman lasers), oscillator-

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amplifier configurations and/or waveguides. SRS generation can be intra-cavity or extra-cavity. Long fiber lengths enable low Raman laser thresholds [18].

Raman lasers have the greatest value when they generate wavelengths not available by other means. Raman lasers make eye-safe LIDAR (light detection and ranging) by shifting the 1.06 µm Nd ion lasers to safer longer wavelengths. Raman fiber lasers offer the highest CW output power of any source in the eye-safe infrared: 300 W with 85% efficiency. A yellow 589-nm Raman laser can be used for a laser guide star (sodium beacon for atmospheric correction) in astronomy when combined with adaptive optics. The yellow wavelength can be achieved by pumping a barium tungstate (BaWO4) Raman emitter placed inside a Q-switched Nd:YAG laser; the Stokes output is at 1180 nm and is then frequency- doubled. Medical lasers also want yellow/orange wavelengths, not available from other lasers. The Raman laser microprobe will be discussed later. Diamond has also produced a Raman laser. It remains to be seen how many of the different Raman laser types will be commercially practical. The largest Raman shifts come from pressurized hydrogen and methane, which have the advantage that, as gases, phasematching is not a major problem. In gases there's no self- focusing, Brillouin scattering or anti-Stokes to worry about (unlike in solids). However, pressurized gases are not always easy to work with. These are used in specialized high-power applications only.

WHITE LIGHT CONTINUUM

One last source of new wavelengths comes from self-phase modulation and four-wave mixing (FWM) of ultra-short optical pulses in fibers (or water). Picosecond pulses in water or femtosecond laser pulses transmitted down fibers are frequency-broadened by these nonlinear processes into a white-light spectrum. This white-light source, covering the entire visible range, down into the infrared and even into the UV, is particularly valuable for ultra-fast excite-probe spectroscopy [19].

NLO FOR PULSING LASERS

Nonlinear optics can create short laser pulses either by Q-switching or mode-locking. Traditional laser cavities contained a rod-shaped crystal along with a nonlinear element (or nonlinear mirror). More recently, diode-pumped microchip lasers have been shown to provide compact, robust sources with a nonlinear Q-switch element to provide high instantaneous power, enough to efficiently generate second harmonic in a phase-matched $\chi 2$ crystal [20].

MODE-LOCKING

Locking all the longitudinal modes in a highly multimode laser produces much shorter pulses from several ps to fs, depending on the bandwidth of the gain medium. This can be done by NLO using saturable absorbers that produce sub-ps pulses from Nd-doped glass and ~10 ps pulses from Nd:YAG. SESAMs create fs pulses from Ti:sapphire lasers; an alternative nonlinear mechanism for these lasers is Kerr-lens mode-locking [21]. The competition to passive NLO mode-locking is active acousto-optic mode-lockers, although this requires tight frequency control.

SOLITONS

The soliton crystal exhibits features of a linear and nonlinear optical pattern at the same time and is insensitive to the initial laser power fluctuations. Another commercial pulsed laser using NLO is the soliton laser, which has the advantage of ultra-stable operation – high repeatability with clean transform-limited pedestal-free pulses. A practical fiber-based fs soliton laser operates at 1.5 µm, the important wavelength for telecommunications [22].

FEMTOSECOND LASER PULSES

Femtosecond lasers could not have been developed without a way to characterize the pulses they emit. Instrumentation that measures both the amplitude and phase of fs pulses requires NLO. The auto correlator has been key, not only to the development of fs technology, but also to the on-going characterization of fs pulses [23]. The length of the pulse overlap in physical space determines its length in time. Pulse-overlap monitoring requires a NLO process (usually SHG) to separate true pulse length from simple interferometry, which only measures spectral width. Without NLO, the entire field of ultra-fast optics would be severely hampered.

SPATIAL AND FREQUENCY CONTROL OF LASERS

The NLO process of phase conjugation has been used for laser beam clean-up, reducing both

spatial and frequency modes. The Stokes light retro-reflected by stimulated Brillouin scattering (SBS) within a fiber will remove aberrations and be diffraction-limited. SBS is used to clean up the spatial and frequency of the pump laser. SBS may limit the power achievable through a single fiber, but it also pr ovides a means of coherently combining multiple beams. SBS locks the phases from parallel

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amplifiers by generating a phase conjugate reflection that propagates back through the amplifiers in a second pass, reconstructing the initial phase profile [24].

The Brillouin laser is a highly coherent light source. One example demonstrates a 20 dB reduction of RIN and frequency noise compared to the narrow-linewidth Er-doped fiber laser pump source. Stable operation requires active stabilization to lock resonance between the pump laser frequency and the Brillouin cavity mode.

IMAGING NONLINEAR PROCESSES

Combining microscopy with NLO changes in materials can be particularly valuable. Using confocal microscopy, biological systems and processes can be analyzed in vivo at the microscopic level. NLO offers higher resolution images and localized functionality. Many of the NLO processes discussed above can be combined with imaging through a confocal microscope: SHG, THG, CARS, and SRS. Because it requires phase-matching, SHG can give additional information on structural data, by separating out different components in tissue without specific staining. SRS can identify micr oscopic local changes in chemical composition [25].

INFORMATION TECHNOLOGY

The dominant information technology impacted by NLO is fiber optic telecommunications. As the use of optical sensors is rapidly developing, NLO shows up in various ways; today, however, it appears that major inroads have not yet been made by NLO technology. As far as signal processing and data storage are concerned, many suggestions have been made, but very few have been commercialized [26].

NLO IN TELECOMMUNICATIONS

Soon after fiber optic telecommunications were introduced, NLO was found to be the fundamental limit to the amount of data that can be transmitted on a single optical fiber. As laser power levels increase, NLO limits data rates, transmission lengths, and the number of wavelengths that can be simultaneously transmitted. NLO showed up first in undersea installations, where fiber lengths were the longest. It is now known that NLO must be considered whenever designing state-of-the-art fiber optic systems. After transmission systems have been designed to overcome basic linear attenuation and dispersion, then NLO becomes important [27].

NLO IN DATA STORAGE

Ordinary interferometry is generally a linear process. Data storage by holography would not, then, be a process that NLO can claim for itself. Compact disk masters were initially made with an argon laser, and the holes were created thermally. Again, not a nonlinear process. The holes in today's high resolution DVD's, however, require much a higher resolution manufacturing process, undoubtedly using the multi-photon ionization microfabrication [28]. Thus NLO can claim an impact on DVD's. The impact of NLO may eventually be seen with storage of data in three dimensions (rather than the 2D of CD's). Efforts to store data using the photo-refractive effect in lithium niobate have not achieved commercial success. Research continues on 3D digital data storage using other NLO processes, such as spectral hole burning, which unfortunately requires cryogenic temperatures.

NLO IN 3D DISPLAY

In recent years, 3D video images have become increasingly popular. A role for NLO appears to be in real-time 3D image formation [29]. University of Arizona has shown that 3D holographic images can be recorded using polymer films made photorefractive by applying a lateral field and relying on a nonlinear refractive index and/or absorption of a chromophore. A new doped-polymer material has been developed for a holographic 3D display capable of refreshing images every two seconds, thereby demonstrating telepresence. Proposed applications include telemedicine, prototyping, advertising, updatable 3D maps and entertainment. It will probably be a while, however, before these early-stage systems will be seen in commercial markets.

NLO SENSORS

Many of today's optical sensors are based on optical fibers, where NLO may begin to play a role. Brillouin fiber sensors are sensitive to a number of variables, and Raman fiber sensors can measure temperature. A variety of nonlinear sensors seem to be coming on the market, but very often the technical details of these sensors are proprietary [30].

II. CONCLUSION

An NLO material is a compound in which a nonlinear polarization is invoked on application of an intense electric field. The understanding of the nonlinear polarization mechanisms and their relation to the structural characteristics of the materials has been considerably improved. Optical solitons, optical switching and memory by NLO effects, which depend on light intensity, are expected to result in the realization of crucial optical devices in optical fiber communication (OFC) and optical computing which make the maximum use of light characteristics such as parallel and spatial processing capabilities and high speed. Second order NLO materials have wide variety of applications in frequency doubling, parametric amplification, parametric oscillation, frequency up conversion, difference frequency generation etc. Third order NLO materials finds applications in optical switching, optical data processing, optical communications, optical logic gates, nonlinear spectroscopy, coherent UV-light generation, optical limiting, passive laser mode-locking, waveguide switches and modulators.

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