7

Lasers and their Applications

Debabrata Goswami[1]
Indian Institute of Technology Kanpur,
Kanpur-208016, India

ABSTRACT

Ever since the advent of the first LASER (acronym for Light Amplification by Stimulation Emission of Radiation) in 1960, there has been a steady increase in the application of lasers. Applications have kept on becoming more and more diverse as the capability of the lasers have increased. In this chapter we will enumerate and classify many of the applications of lasers and then go on to discuss in more detail some of the more modern applications.

1. Introduction

Lasers deliver coherent, monochromatic, well-controlled, and precisely directed light beams. A priori, therefore, lasers would seem tobe poor choices for general-purpose illumination, however, they are ideal for concentrating light in space, time, or particular wavelengths. Lasers have been regularly used to measure, cut, drill, weld, read, write, send messages, solve crimes, burn plaque out of arteries, and perform delicate eye operations. Over and over again the laser has proved to be an extremely practical tool. Nevertheless, lasers have also proved their usefulness in non-practical applications, especially in the realm of art and entertainment. Lasers are involved in almost all aspects of these fields, from "light shows" to Compact Discs (CDs) and Digital Video Discs (DVDs), to special effects in the movies. Some other commonplace application of lasers are as Laser pointers, barcode scanners, laser printers, etc. Still, much of the important modern day celebrated applications lie in the fiber-optic communication, laser machining and fabrication, trace element detection, laser metrology and medical imaging.

2. Application Categories

Broadly speaking, applications of lasers can be put into two categories, one is based on the wave or particle characteristics of light while the other is governed by the light matter interaction characteristics. Thus, most laser applications fall in-to one of a few broad categories: (1) transmission and processing of information, (2) precise delivery of energy, and (3) alignment, measurement, and imaging. These categories cover diverse applications, from pinpoint energy delivery for delicate surgery to heavy-duty welding and from the mundane alignment of suspended ceilings to laboratory measurements of atomic properties. Simple light wave based properties result in interference, diffraction, reflection, refraction, etc. type properties, while particle like properties are based on light scattering. So, concepts like, why the sky is blue or the ocean is blue or how putting face powder makes one look brighter as compared to putting oil on face are all based on light scattering problems. Light matter interaction, on the other hand, leads to another large gamut of applications, starting from simple linear absorption to the very concept of the lasing action.

3. Some Specific Applications

3.1 Optical Communication and Storage

The ability to focus laser beams onto very small spots and to switch them on and off billions of times per second makes lasers important tools in telecommunications and information processing. In laser supermarket scanners, a rotating mirror scans a red beam while clerks move packages across the beam. Optical sensors detect light reflected from striped bar codes on packages, decode the symbol, and relay the information to a computer so that it can add the price to the bill. Similarly, tiny, inexpensive semiconductor lasers read data from a growing variety of optical compact disc formats to play music, display video recordings, and read computer software. Audio compact discs, using infrared lasers, were introduced around 1980; CD-ROMs (compact disc read-only memory) for computer data soon followed. Newer optical drives use more powerful lasers to record data on light-sensitive discs called CD-R (recordable) or CD-RW (read/write), which can be played in ordinary CD-ROM drives. DVDs (digital video, or versatile, discs) work similarly, but they use a shorter-wavelength red laser to read smaller spots, so the discs can hold enough information to play a digitized motion picture. A newer generation of discs called Blu-ray uses blue-light lasers to read and store data at an even higher density (Fig. 1).

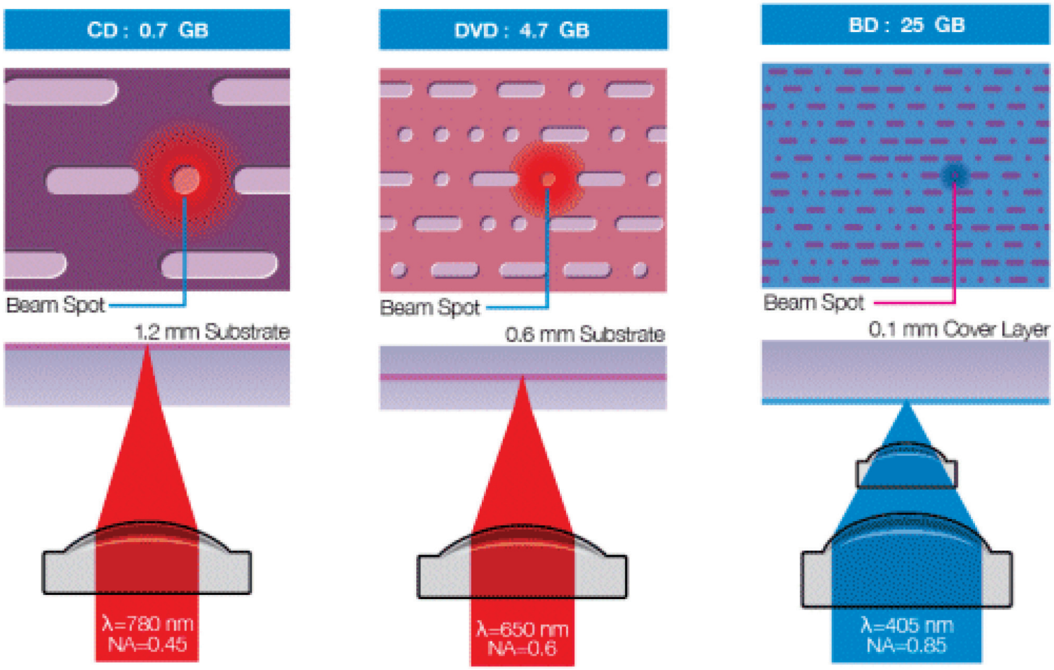


Figure 1: (Color online) Schematic diagram of the comparison between the CD, DVD and Blue-Ray disk for data storage using different laser wavelengths.

Fiber-optic communication systems that transmit signals more than a few kilometers also use semiconductor laser beams. The optical signals are sent at infrared wavelengths of 1.3 to 1.6 micrometers, where silica glass fibers are most transparent. This technology has become the backbone of the global telecommunications network, and most telephone calls traveling beyond the confines of a single town go part of the way through optical fibers.

3.2 Laser Machining and Cutting

Laser energy can be focused in space and concentrated in time so that it heats, burns away, or vaporizes many materials. Although the total energy in a laser beam may be small, the concentrated power on small spots or during short intervals can be enormous. Although lasers cost much more than mechanical drills or blades, their different properties allow them to perform otherwise difficult tasks. A laser beam does not deform flexible materials as a mechanical drill would, so it can drill holes in materials such as soft rubber nipples for baby bottles. Likewise, laser beams can drill or cut into extremely hard materials without dulling bits or blades. Laser machining is not dependent on the material hardness but on the optical properties of the laser and the optical and thermo-physical properties of the material. For example, lasers have drilled holes in diamond dies used for drawing wire.Several recent research have shown that laser cutting is best achieved with ultrafast lasers (Fig. 2), as the material only ablates and does not get a chance to melt under such ultrafast time scale interactions.

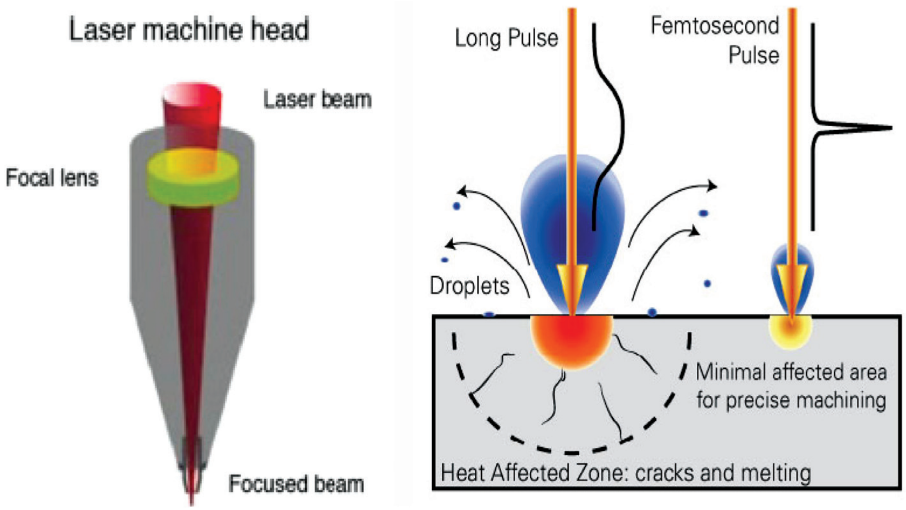


Figure 2: (Color online) Schematic diagram of laser machining head and its machining action under the comparison of long pulse versus femtosecond (10-15 second) laser pulse machining.

3.3 Military and Defense Applications

Scientists have shown that lasers can concentrate extremely high powers in either pulses or continuous beams. Major applications for these high-power levels are fusion research, nuclear weapons testing, and missile defense. Extremely high temperatures and pressures are needed to force atomic nuclei to fuse together, releasing energy. Intense laser pulses could theoretically produce these conditions by heating and compressing tiny pellets containing mixtures of hydrogen isotopes, which suggests using these "micro-implosions" both to generate energy for civilian use as well as to simulate the implosion of a hydrogen bomb, which involves similar processes. Since then, a series of lasers have been built to test and refine these theories. High-energy lasers offer a way to deliver destructive energy to tar-gets at the speed of light, which is very attractive for fast-moving targets such as nuclear missiles. In 1970, military laser range finders were developed to measure the distance to battlefield targets accurately. Military researchers have tested high-energy lasers for use as weapons on land, at sea, in the air, and in space, although no high-energy lasers have been placed in orbit. Experiments have shown that massive lasers can generate high powers; however, tests have also shown that the atmosphere distorts such powerful beams, causing them to spread out and miss their targets. These problems haveslowed research on laser weapons, though inter-est continues in laser developments to defend against smaller-scale missile attacks.

3.4 Metrological and Geophysical Applications

Surveyors and construction workers use laser beams to draw straight lines through the air. The beam itself is not visible in the air except where scattered by dust or haze, but it projects a bright spot on a distant object. Surveyors bounce the beam off a mirror to measure direction and angle. The beam can set an angle for grading irrigated land, and a rotating beam can define a smooth plane for construction workers installing walls or ceilings. Pulsed laser radar can measure distance in the same manner as microwave radar by timing how long it takes a laser pulse to bounce back from a distant object. For example, in 1969 laser radar precisely measured the distance from the Earth to the Moon. Laser range finding is now widely used for remote sensing. Instruments flown on aircraft can profile the layers of foliage in a forest, and the Mars Global Surveyor used a laser altimeter to map elevations on the Martian surface.

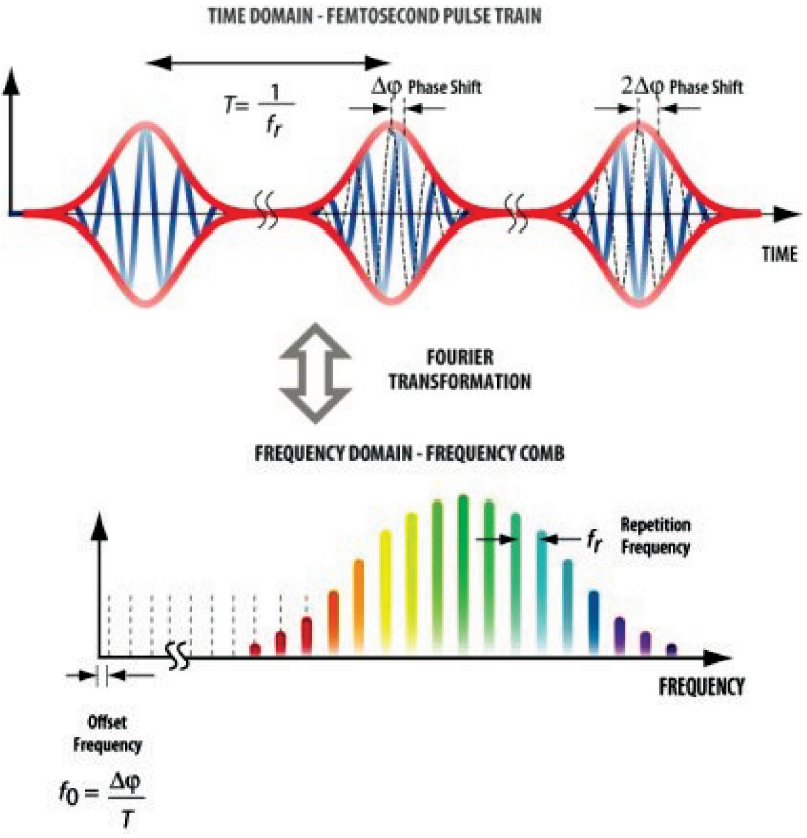


Figure 3: (Color online) A train of stabilized laser pulses generates a comb of sharp spectral lines defined by two radio frequencies: the comb spacing (f_{rep}) and an offset (f_0).

Mode-locked femtosecond lasers emit tens of thousands of discrete laser lines with a frequency-spacing precisely given by the laser repetition rate f_{rep}. Their output is thus commonly referred to as a frequency comb where each tooth is essentially an integer multiple of f_{rep}. It is this simplicity by which a frequency comb directly links the optical (hundreds of terahertz) and the radio (hundreds of Mega-hertz) frequency domains separated by several decades that are practically governed by very different technologies (Fig. 3),which has made frequency combs very powerful and invaluable tools. The 2015 Physics Nobel Prize was awarded to Theodor Hänsch and John Hall for developing this idea. Frequency combs enable precision optical frequency measurements much in the same way as a ruler is used to measure a distance. They serve in many laboratories worldwide to perform fundamental physics experiments such as measurements of the drift of fundamental natural constants. They are used to perform massively parallel precision optical spectroscopy or to synthesize microwave signals with unprecedentedly low phase-noise. Frequency combs also support the development of novel superior optical atomic clocks, by functioning as their clockwork, which may eventually lead to such practical advances as a more precise Global Positioning System (GPS) navigation.

3.5 Laser Imaging and Holography

The coherence of laser light is crucial for interferometry and holography, which depend on interactions between light waves to make extremely precise measurements and to record three-dimensional images. The result of adding light waves together depends on their relative phases. If the peaks of one align with the valleys of the other, they will interfere destructively to cancel each other out; if their peaks align, they will interfere constructively to produce a bright spot. This effect can be used for measurement by splitting a beam into two identical halves that follow different paths. Changing one path just half a wavelength from the other will shift the two out of phase, producing a dark spot. This technique has proved invaluable for precise measurements of very small distances. Holograms are made by splitting a laser beam into two identical halves, using one beam to illuminate an object. This object beam then is combined with the other half—the reference beam—in the plane of a photographic plate, producing a random-looking pattern of light and dark zones that record the wave front of light from the object (Fig. 4). Later, when laser light illuminates that pattern from the same angle as the reference beam, it is scattered to reconstruct an identical wave front of light, which appears to the viewer as a three-dimensional image of the object. Holograms now can be mass-produced by an embossing process, as used on credit cards, and do not have to be viewed in laser light.

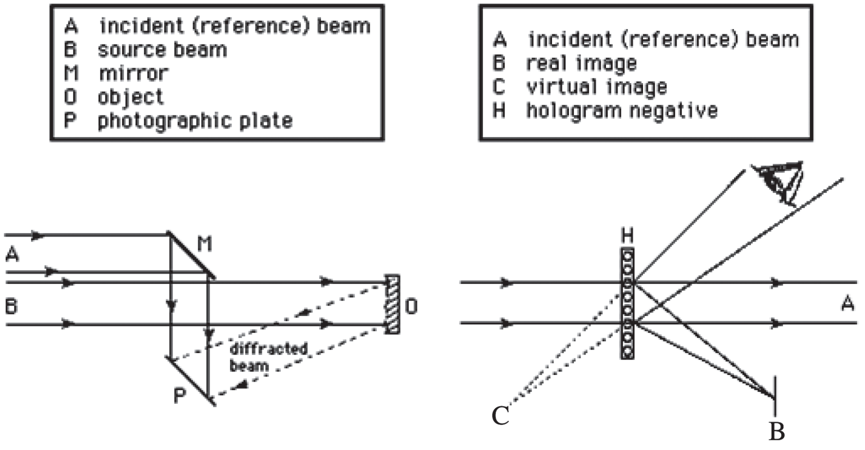
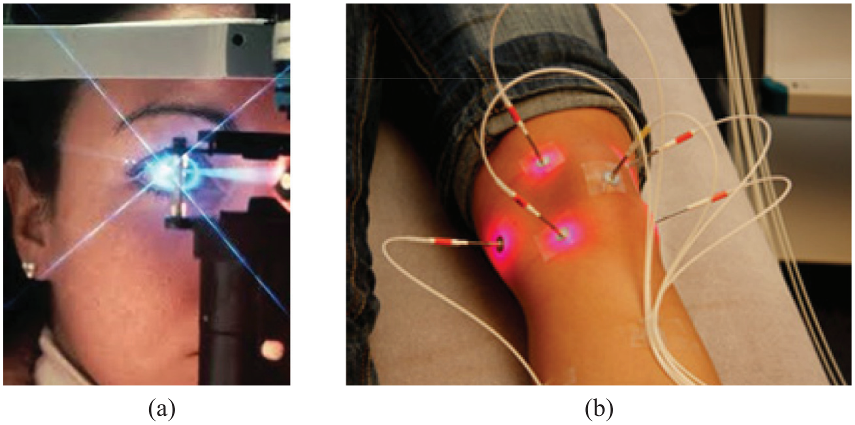


Figure 4: Schematic of Holography process where the laser beam is split into three components. First two beams are needed to create the hologram which is viewed with the help of the third.

3.6 Medical Applications

Surgical removal of tissue with a laser is a physical process similar to industrial laser drilling. Carbon-dioxide lasers operating at 10.6 micrometers can burn away tissue as the infrared beams are strongly absorbed by the water that makes up the bulk of living cells. A laser beam cauterizes the cuts, stopping bleeding in blood-rich tissues such as gums. Similarly, laser wavelengths near one micrometer (Neodymium-YAG Laser) can penetrate the eye, welding a detached retina back into place, or cutting internal membranes that often grow cloudy after cataract surgery (Fig. 5a). Less-intense laser pulses can destroy abnormal blood vessels that spread across the retina in patients suffering from diabetes, delaying the blindness often associated with the disease. Ophthalmologists surgically correct visual defects by removing tissue from the cornea, reshaping the transparent outer layer of the eye with intense ultraviolet pulses from Excimer Lasers.



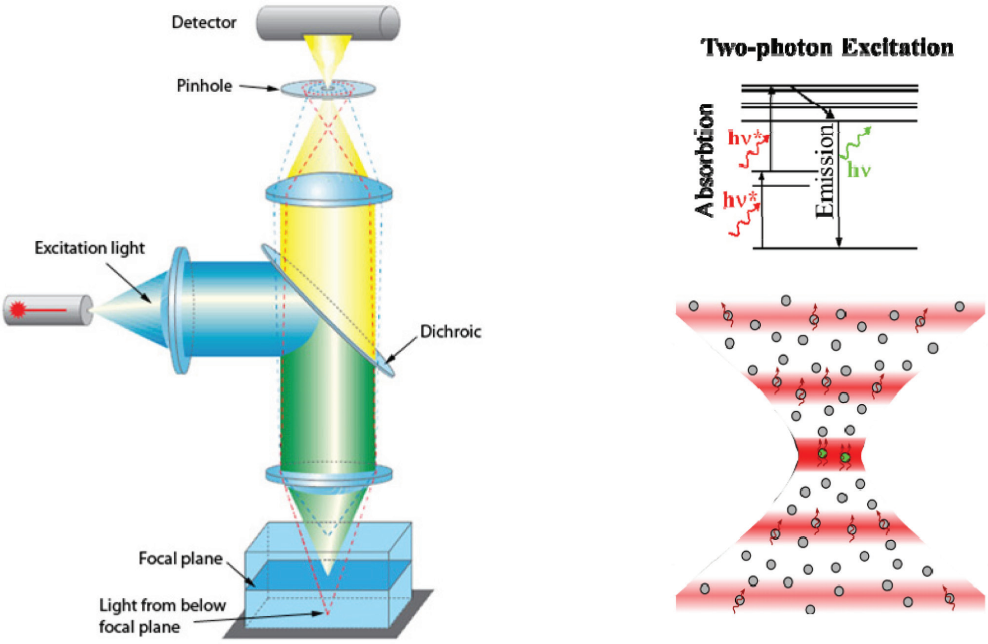
(a) (b)

Figure 5: (Color online) (a) Schematic of Laser Eye Surgery. (b) Laser energy delivery to precise spots in joints for arthroscopic surgery.

Laser light can be delivered to places within the body that the beams could not otherwise reach through optical fibers similar to the tiny strands of glass that carry information in telephone systems. One important example involves threading a fiber through the urethra and into the kidney so that the end of the fiber can deliver intense laser pulses to kidney stones. The laser energy splits the stones into fragments small enough to pass through the urethra without requiring surgical incisions. Fibers also can be inserted through small incisions to deliver laser energy to precise spots in the knee joint during arthroscopic surgery (Fig. 5b). Another medical application for lasers is in the treatment of skin conditions. Pulsed lasers can bleach certain types of tattoos as well as dark-red birthmarks called port-wine stains. Cosmetic lasertreatments include removing unwanted body hair and wrin-kles.

3.7 Biomedical Imaging and Superresolution

Confocal microscopy (Fig. 6) is a ubiquitous imaging tool for imaging thick specimen in a wide range of investigations in biological, medical and material sciences.



(a) (b)

Figure 6: (Color online) Schematic of a (a) confocal microscope showing the critical placement of confocal pinhole to ensure all out of plane light is blocked before the detector to result in a sharp image from a thick specimen. (b) For two-photon microscopy, self-aperture occurs.

It uses UV or visible light for the single photon excitation of fluorophore from ground state to the excited state followed by deactivation through fluorescence emission which is detected through high quantum efficiency photomultiplier tube (PMT) in the range of near ultraviolet, visible and near infrared spectral region. The basic difference of confocal Light Scanning Microscope with the conventional optical microscope is the confocal aperture arranged in a plane conjugate to the intermediate image plane and thus, to the object plane of the microscope. The PMT can only detect the light that passed the pinhole. As the laser beam is focused to a diffraction limited spot, which illuminates only a point of the object at a time, the point illuminated and the point observed are situated in conjugate planes, i.e. they are focused onto each other. The perfection of focused beam which is connected to the resolution has always been a matter of concern in the far-field fluorescence microscopy. Still, optical microscopy remains the best choice for monitoring live specimens despite the resolution advantage of, say electron microscopes, since the energy deposited in electron microscopy adversely affects the viability of live specimens. This practical compromise implicitly sets resolution enhancement as one of the most important development in optical microscopy. For a single fluorescent molecule, Ernst Abbe defined a minimum diffraction-limited image having lateral (x,y) and axial (z) dimensions defined by the excitation wavelength (λ) refractive index of the imaging medium (η), and the angular aperture (α) of the microscope objective as:

$$\text{Resolution}_{x,\,y} = \lambda \big/ 2[\eta \cdot \sin(\alpha)] \tag{1}$$

$$\text{Resolution}_{x,\,y} = 2\lambda \big/ [\eta \cdot \sin(\alpha)]^2 \tag{2}$$

where the combined term η • sin(α) is known as the objective numerical aperture (NA). Objectives commonly used in microscopy have a numerical aperture that is less than 1.5 (although new high-performance objectives closely approach this limit), restricting the term α in Equations (1) and (2) to less than 70 degrees. Therefore, the theoretical resolution limit at the shortest practical excitation wavelength (approximately 400 nanometers when using an objective having a numerical aperture of 1.40) is around 150 nanometers in the lateral dimension and approaching 400 nanometers in the axial dimension. In practical terms for imaging living cells, these values are approximately 200 and 500 nanometers, respectively. Thus, structures that lie closer than 200 to 250 nanometers cannot be resolved in the lateral plane using either a wide field or confocal fluorescence microscope and is known as the Abbe's resolution limit (Fig. 7a).

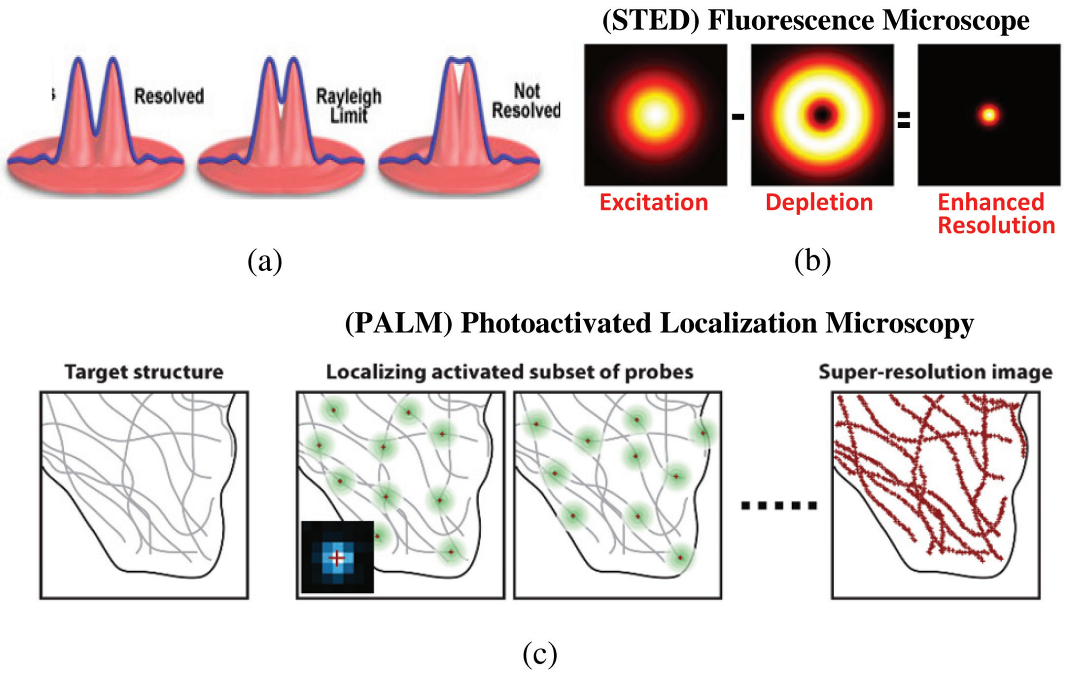


Figure 7: (Color online) (a) Schematic of Abbe's diffraction resolution limit using the Rayleigh criteria where the first diffraction minimum of the image of one source point coincides with the maximum of another. (b) In stimulated emission depletion fluorescence (STED) Microscope, the laser spot size is made smaller by using the depletion effect of fluorophore. (c) In photoactivated localization microscopy (PALM), superresolution is achieved using individual fluorophore that are photoactivated at different times as probe.

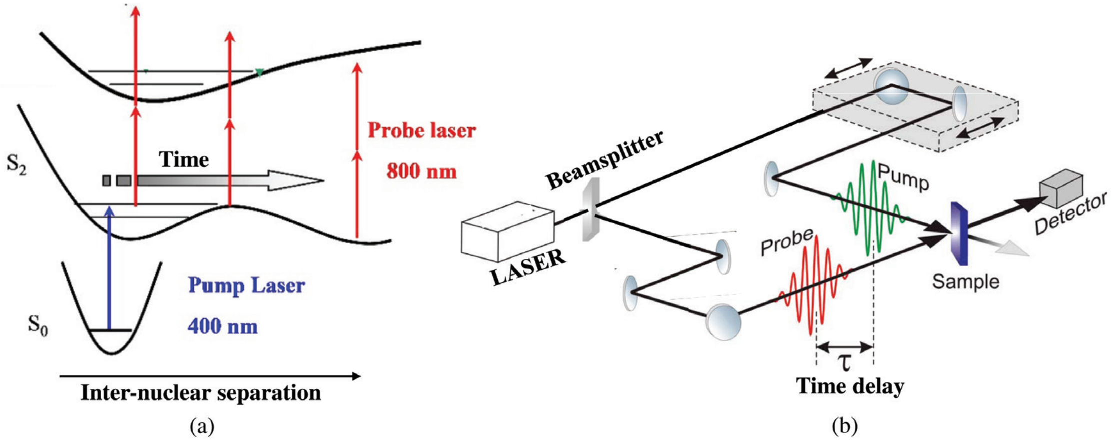
The 2014 Nobel Prize celebrated the development of super-resolved fluorescence microscopy that has made visible essential details and movements of the molecules of life. This development conquered the physical limit, described by Ernst Abbe in 1873, implying that objects of smaller dimensions than half of the wave length of light cannot be discerned by opticalmicroscopy. The Prize recognized the very first two ways to surpass Abbe's diffraction limit. The first method to by-pass Abbe's limit involved two laser beams shining on the structure of interest in a fluorescence microscope. One beam excites the fluorescent molecules in a volume determined by Abbe's limit (Equations (1) and (2)). The other beam rapidly brings all the excited molecules, except those in a volume that can be made arbitrarily small, to their ground state before they can emit a photon. When both beams jointly scan the structure, an image with resolution better than Abbe's limit emerges. Stefen W. Hell demonstrated this experimentally in 2000 and called it STimulated Emission Depletion (STED) microscopy (Fig. 7b). In the second approach, William Moerner and Eric Betzig developed a method where the biological structure is labelled with optically activatable Green Fluorescence Protein (GFP). A weak light pulse activates a small fraction of the GFP molecules, so that all molecules in this fraction are further apart than Abbe's limit, and thus can be localized with super-precision. Then, yet another small fraction of the GFP molecules are activated so that also they can be super-localized. This is repeated until a large number of such images have been created. Finally, all these images are combined into one super-resolved image with complete structural information. They demonstrated this method first in 2006 and called it Photo Activated Localization Microscopy (PALM) (Fig. 7c).

4. Fundamental Research Applications

The ability to control laser wavelength and pulse duration precisely has proved invaluable for fundamental research in physics and other sciences. Lasers have been particularly important in spectroscopy, the study of the light absorbed and emitted when atoms and molecules make transitions between energy levels, which can reveal the inner workings of atoms. Lasers can concentrate much more power into a narrow range of wavelengths than other light sources, which makes them invaluable in analyzing fine spectroscopic details.

For example, simultaneously illuminating samples with laser beams coming from opposite directions can cancel the effects of the random motions of atoms or molecules in a gas. This technique has greatly improved the precision of the measurement of the Rydberg constant, which is critical in calculations of atomic properties, and it earned Arthur Schawlow a share of the 1981 Nobel Prize for Physics. Nicolaas Bloembergen shared the prize for developing other types of high-precision laser spectroscopy. Since that early work, laser spectroscopy has expanded considerably. Laser pulses have been used to take snapshots of chemical reactions as they occur, on time scales faster than atomic vibrations in a molecule.

Femtochemistry—the study of chemical processes femtosecond (10–15 second) timescale—was pioneered by Zewail when his research group established methodology for following the intricacies of chemical transformations as reactants evolve into products through fleeting reaction intermediates. In 1987, Zewail and co-workers performed the first femtosecond time-resolved spectroscopic study of a molecular dissociation using flashes of laser light that last for a few femtoseconds. A reaction can be over in 1,000 femtoseconds, so lasers capable of emitting pulses lasting a hundred femtoseconds or less are needed to probe the details of the process. In the 1970s, Charles Shank and colleagues at Bell Laboratories (Murray Hill), New Jersey developed liquid dye lasers capable of producing pulses of just a few hundred femtoseconds. Liquid dye lasers use fluorescent organic dyes to produce laser light. For shorter the laser pulse required, the larger the range of frequencies of light it must contain. Shank and his colleagues were able to restrict the pulses to the very short timescales by using a range of dyes, each of which emits light of a different frequency, and by the early 1980s, they furthered the technology to a level that pulses of tens of femtoseconds were possible. Zewail built a version of the Bell Labs laser in 1987 that was capable of producing pulses of 60 femtoseconds and applied it to study the dissociation of iodine cyanide (ICN) into iodine and cyanide. ICN molecules absorb different frequencies of light as the bond between the iodine atom and cyanide molecule stretches. Zewail took a series of snapshots of the process by sending in probe pulses at different times after the initial pulse and showed that the bond broke after around 200 femtoseconds, by which point the iodine atom and cyanide molecule had been stretched by about 5 angstroms. In itself, that finding was of limited interest, but the proof that femtosecond spectroscopy worked was a huge breakthrough. Twelve years later, Zewail was awarded the 1999 Nobel Prize in chemistry. This simplest approach to femtochemistry is known as the pump–probe spectroscopy where femtosecond lasers were used as ‘cameras’ to study the intermediate stages of chemical reactions (Fig. 8).



(a) (b)

Figure 8: (Color online) Schematic of Zewail pump-probe spectroscopy for (a) a generic molecular dissociation model with (b) pump and probe pulses generated from the same laser that are measured at different time delays between them.

In this general “pump-probe” method, two or more optical pulses with variable time delay between them are used to investigate the processes happening during a chemical reaction. The first pulse (pump) initiates the reaction, by breaking a bond or exciting one of the reactants. The second pulse (probe) is then used to interrogate the progress of the reaction a certain period of time after initiation. Every atom or molecule has a unique set of frequencies of light that it can absorb, so by looking for frequencies that are missing from the pulse, chemists can determine what chemical species are present, and in what quantities. Atoms or molecules can also re-emit light that they have absorbed, again at specific frequencies. As the reaction progresses, the response of the reacting system to the probe pulse will change. By continually scanning the time delay between pump and probe pulses and observing the response, researchers can reconstruct the progress of the reaction as a function of time. These techniques have given chemists new ways to understand chemical physics though their application has now been expanded to many more research fields. In biological studies, for instance, application of femtochemistry has helped to elucidate the conformational dynamics of stem-loop RNA structures.

Despite the wealth of discoveries made possible by femtosecond techniques, some aspects of chemistry remain inaccessible. Whatever the probe pulse used, femtosecond techniques provide little information about the position of electrons within their orbits. Electrons move a thousand times faster than atomic nuclei, hence recording their motion requires thousand times shorter (10^{-18} second), *i.e.*, attosecond-scale, shutter time. According to classical theories, an electron can orbit a hydrogen atom in a fraction of a femtosecond, so pulses of just a few hundred attoseconds would be needed to track each electron. The lower limit for a pulse of visible light, defined by the duration of a single cycle of the wave, is 3 femtoseconds. But X-rays have shorter wavelengths, and pulses down to as little as 50 attoseconds are possible in principle. Some researchers believe attochemistry may soon be possible from the analogy that just as the amplitude variation of a femtosecond pulse triggers and probes nuclear motion in Zewail's femtosecond photography, an attosecond ultraviolet or X-ray pulse coming in synchrony with a few-cycle laser pulse of controlled waveform pulse may be used for starting or capturing electronic motion in real time. The role of the attosecond "starter gun" or "shutter" can alternatively be played by the central half cycle of the controlled electric field of a few-cycle wave of visible light. This can, for instance, liberate an electron from an atom, and an attosecond ultraviolet pulse can take snapshots of the electronic motion unfolding inside the atom after its ionization. The snapshots in this case appear in the form of energy distributions of the photons of the attosecond pulse transmitted through ionized atoms, from which the instantaneous state of the electrons can be inferred. If desirable attosecond pulses can be generated, a host of new phenomena will be open up. One example is the movement of electrons in excited molecules. A molecule is more likely to react when one of its electrons is in an excited state, however, the electron may fall back to its ground state before the reaction occurs. A study of the movement of excited electrons may help explain why certain reactions occur, whereas others fail. The latest in a line of advances that have redrawn the limits of chemical sciences would be attochemistry. Interestingly, the immeasurable will have to be redefined once again if attosecond techniques do become reality.

One of the other areas where researchers are using such femtosecond techniques are to control chemical reactions. The enhanced knowledge of the molecular systems and dynamics as possible through femtochemistry has rejuvenated the quest to control chemistry, especially molecular dynamics in the later part of the twentieth century. Birth of coherent control was originally spurred by the theoretical understanding of the quantum interferences that lead to energy randomization and experimental developments in ultrafast laser spectroscopy. Coherent control is the ability to control the dynamics at various stages of a process as it evolves under the effect of a coherent source. Many of the frequencies constituting the ultrafast pulse can simultaneously excite many coherent transitions to the excited states, and a capability to manipulate them with the shaped pulses lead to the interesting results. The theoretical predictions on control of reaction channels or energy randomization processes are still more dramatic than the experimental demonstrations, though this gap between the two has consistently reduced over the recent years with realistic theoretical models and technological developments. Experimental demonstrations of arbitrary optical pulse shaping have made some of the previously impracticable theoretical predictions possible to implement. Starting with the simple laser modulation schemes to provide proof-of-the-principle demonstrations, feedback loop pulse shaping systems have been developed that can actively manipulate some atomic and molecular processes. This tremendous experimental boost of optical pulse shaping developments (Fig. 9) has prospects and implications into many more new directions, including terabit/sec data communications.

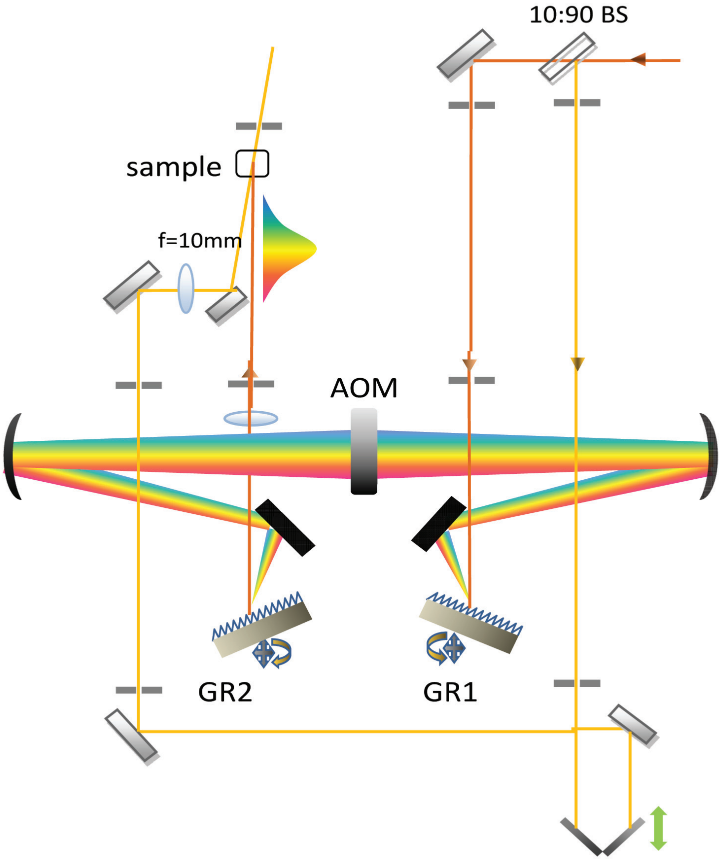
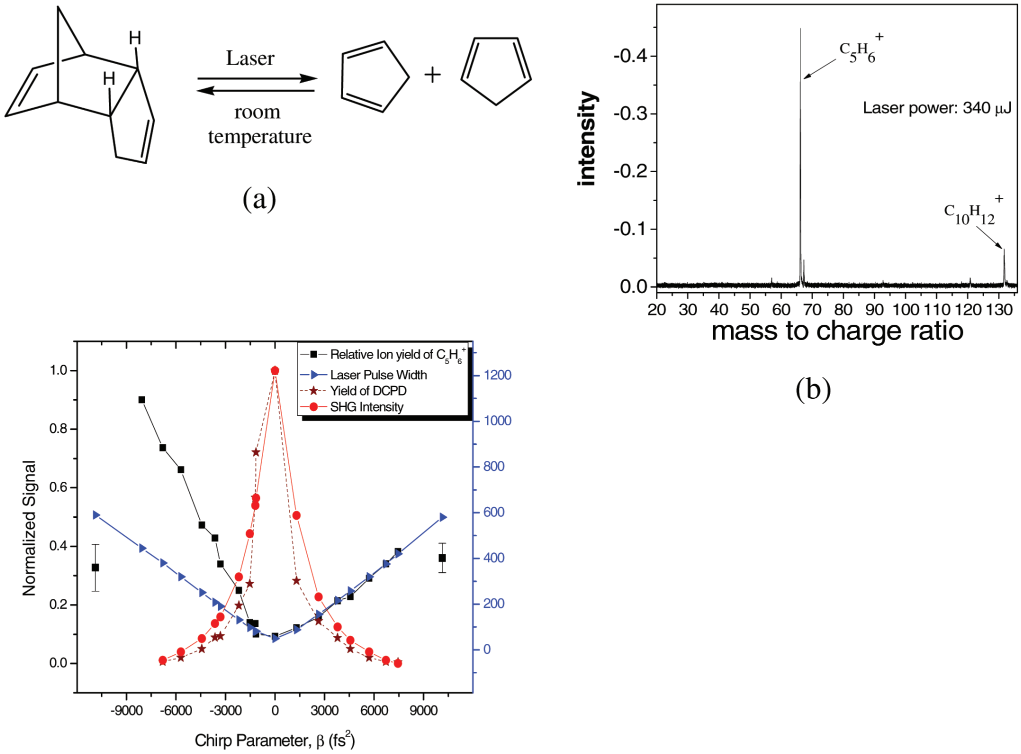


Figure 9: (Color online) Schematic diagram of a Fourier Transform pulse shaper with AOM (acousto-optic modulator) with a pump probe experimental setup on a sample.

The fundamental aspects of laser-matter interactions using arbitrary pulse shaping has been intriguing andultrafast laser pulse shaping applications have been inves-tigated in gaseous and liquid phase molecular dynamics, optoelectronics, nonli-near optics and optical communication, biologically relevant multi-photon fluo-rescence microscopy and optical trapping. These diverse fields have been knit together for quantum information processing. The importance of laser pulse mani-pulation for controlled molecular interactions has resulted in the development of more pragmatic goals and approaches to the age-old dream of "laser-selective chemistry". Availability of powerful ultrafast laser sources over a wide range of wavelengths and experimental developments of arbitrary optical pulse shaping have been key technological factors in providing proof-of-principle demonstra-tions. Pulse shaping essentially involves control over the amplitude, phase, fre-quency and/or inter-pulse separation. Complex pulse shaping aims to control one or more of the above-mentioned parameters in a programmable manner, such that the user has complete control. In other words, complex pulse shaping allows gen-eration of complicated ultrafast optical waveforms according to user specification.

An ultrafast laser pulse can be represented as a coherent superposition of many monochromatic light waves within a range of frequencies that is inversely propor-tional to the duration of the pulse. Thus, for instance, a 40fs pulse at 800nm that is commercially available has a spectrum as broad as 30nm. Possibilities of manipulating such an ultrafast coherent bandwidth are nontrivial as it lasts for such an ultrashort duration wherein no modulators work. A creative solution to the problem of slow modulators is the indirect pulse shaping in the frequency domain. In the time domain the filter is characterized by a time response function $g(t)$. The output of the filter $E_{\mathrm{out}}(t)$ in response to an input pulse $E_{\mathrm{in}}(t)$ is given by the convolution of $E_{\mathrm{in}}(t)$ and $g(t)$, such that, $E_{out}(t) = E_{\mathrm{in}}(t) \otimes g(t)$. In the frequency domain, the filter is characterized by its frequency response $G(\omega)$, i.e., $E_{out}(\omega) \times E_{in}(\omega) \times G(\omega)$, where $E_{\mathrm{in}}(t)$, $E_{\mathrm{out}}(t)$ and $g(t)$ and $E_{\mathrm{in}}(\omega)$, $E_{\mathrm{out}}(\omega)$ and $G(\omega)$, respectively are Fourier transform pairs. With a delta function input pulse, the input spectrum $E_{\mathrm{in}}(\omega)$ is unity and the output spectrum is equal to the frequency response of the filter, and thus, due to Fourier transform relations generation of a desired output waveform can be accomplished by implementing a filter with the required frequency response. Control of molecular reaction directs vibronically excited molecular systems into specific reaction pathways. Failure through such molecular control through laser selective excitation arises from decoherence and dephasing of coherence. Minimizing decoherence is also an important challenge towards realizing quantum computing and quantum information. Typical molecular vibrations occur in picoseconds. So it is important to have control parameters in femtoseconds. Population transfer in molecules involves multiple states besides the radiative coupled two labels which undergo quantum interferences resulting in decoherences. Coupling to the non-radiative channels can however be minimized to robustly controlled decoherence through destructive quantum interference between the multiple excitation pathways.

Another attractive approach is the use of simple chirped pulses, which, by con-trast, have been produced routinely at very high intensities and at various different wavelengths for many applications, including selective excitation of molecules in coherent control. Demonstration of control over a symmetric dissociation reaction of dicyclopentadiene into two cyclopentadiene molecules was successful simply with the help of linearly chirped pulses inducing the multiphoton dissociation process in the gas phase (Fig. 10). Typical condensed phase reactions involving solvents are much more complicated and require more complex pulse shaping as discussed.



(a) (b) (c)

Figure 10: (Color online) Linear frequency chirped laser pulse induced control showed in the gas phase dissociation of dicyclopentadiene: (a) Photo-dissociation reaction. (b) The mass fragments corresponding to the reactant and products. (c) Evidence of control as the negative chirp is more efficient in dissociation reaction as compared to the positive chirp.

The subtle forces exerted by laser beams, i.e., radiation pressure or the photon flux has been used to slow and trap atoms, molecules, and small particles. A technique pioneered by the Bell Labs researcher, Arthur Ashkin, “optical tweezers” use a tightly focused horizontal laser beam to trap atoms in the highest light intensity zone, is now used in a variety of research. Other research has also shown that laser illumination can slow the motion of atoms if its wavelength is tuned to a point slightly off the wavelength of peak absorption. The atoms repeatedly absorb photons from the beam and then emit photons in random directions. The photon momentum slows the motion toward the laser beam. Placing the atoms at the junction of six laser beams aimed at right angles to each other slows their momentum in all directions, produces a clump of atoms less than 0.001 degree above absolute zero. Adding a magnetic field improves confinement and can reduce their temperature to less than one-millionth degree above absolute zero. These techniques have led to the creation of a new state of matter, called a Bose-Einstein condensate, which earned Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips the 1997 Nobel Prize for Physics.

One of the more recent developments have been an optical tweezer that is generated with femtosecondlaser (Fig. 11), where the trapped particle is confined in space through temporally instantaneous interaction and provides both spatial and temporal control in trapping. Even for most of the high repetition rate lasers which have been employed for such tweezers (lasers with ~100 femtosecond pulse width at ~100MHz repetition), the light is absent for more often than it is present, much of the observations from such a trapped object reflect the inertial stable condition.

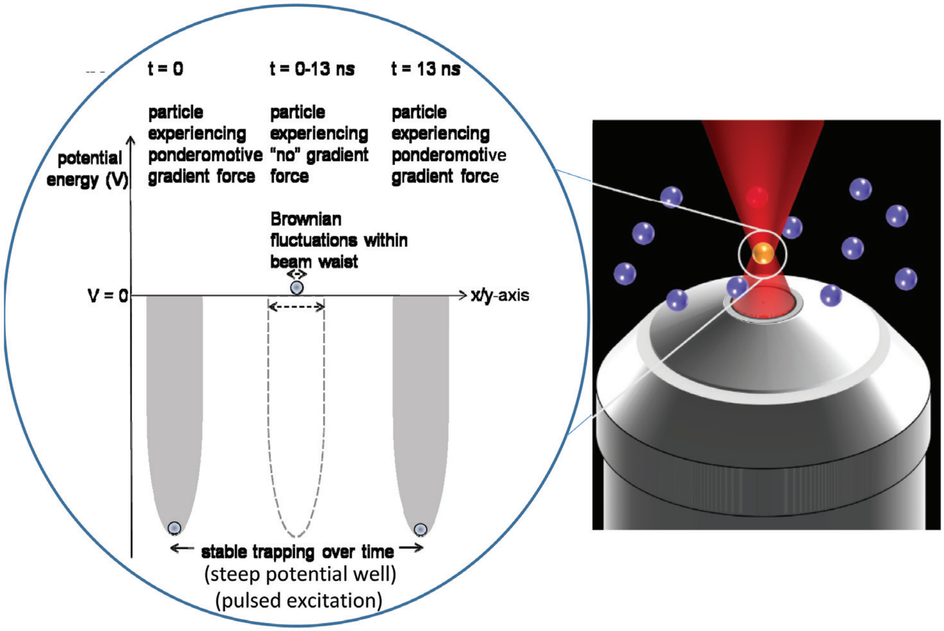


Figure 11: (Color online) Femtosecond pulsed laser tweezer showing the trapped florophore coated nanosphere glowing from two-photon fluorescence. Since it is a pulsed trap, the trap is only present intermittantly. However, as long as the gap between the pulses are not so large that the particle can drift away substantially, the particle remaines trapped.

The main advantage of using femtosecond laser is that in addition to the back-scattering signal of the trapped object, it can generate multi-photon processes like two-photon fluorescence (TPF) that can be used for background free imaging of the trapping process and can efficiently trap and manipulate micro- and nano-objects including living cells, colloidal nano spheres, metallic nano particles, quantum dots etc. in a non-invasive, non-contact fashion. The back ground free detection of trapping is possible as TPF appears at a different wavelength as com-pared to the trapping laser and so can be measured independent of interference of the incident trapping laser. Such an approach has been recently shown to be very effective in measuring very small temperature changes in nanoscale environments accurately.

5. Conclusion

This chapter has provided a glimpse of some of the many applications of lasers. We have deliberately provided more details on some of the recent applications that have been the highlighted in recent literature. We just hope that this would increase the interest of the reader to keep up to the many more laser applications that keep coming up with time.

Acknowledgments

DG thanks DST, MCIT, MHRD, ISRO (India) as well as Wellcome Trust International Senior Research Fellowship for financial supports. Thanks are also due to the incessant support from the PhD students for the re-search done in the lab and Mrs. S. Goswami for patient proof reading.

Referencesand Suggested Readings

1. Gai, X., Choi, D.-Y., Madden, S., and Luther-Davis, B., Materials and Structures for Nonlinear Photonics, Chapter 1 in All-Optical Signal Processing—DataCommunication and Storage Applications. Springer Se-ries in Optical Sciences, Editors: Wabnitz, Stefan, Eggleton, Benjamin J. (Springer, New York, USA 2015)
2. Armstrong, S., All-Optical Storage. Nature Photonics **6**, 636–637 (2012)
3. Sugioka, K. and Cheng, Y., Ultrafast lasers—reliable tools for advanced materials processing. Light: Science & Applications **3**, e149, doi:10.1038 (2014)
4. Diddams, S.A., Jones, D.J., Ye, J., Cundiff, S.T., Hall, J.L., Ranka, J.K., Windeler, R.S., Holzwarth, R., Udem, Th., and Hänsch, T.W.,Direct Link between Microwave and Optical Frequencies with a 300 THz Femtose-cond Laser Comb. Phys. Rev. Lett. **84**, 5102 (2000)
5. Hell, S.W., Nanoscopy with focused Light (Nobel Lecture). Angew. Chem. Int. Ed. **54**, 8054-8066 (2015)
6. Betzig, E., Patterson, G.H., Sougrat, R., Lindwasser, O.W., Olenych, S., Bonifacino, J.S., Davidson, M.W., Schwartz, J.L., and Hess, H.F., Im-aging Intracellular Fluorescent Proteins at Nanometer Resolution. Science **313**, 1642 (2006)
7. Goldsmith, R.H., Moerner, W.E., Watching conformational- and photo-dynamics of single fluorescent proteins in solution. Nature Chemistry **2**, 179–186 (2010)
8. Bloembergen, N., Nonlinear Optics and Spectroscopy. Nobel Lectures, Physics 1981-1990, Editor-in-Charge Tore Frängsmyr, Editor Gösta Eks-pong(World Scientific Publishing Co., Singapore, 1993)
9. Zewail, A. H., Femtochemistry: Ultrafast Dynamics of the Chemical Bond, Vols. 1 and 2 (World Scientific, Singapore 1994)
10. Goswami, D., Optical pulse shaping approaches to coherent control. Phys. Rep. **374**(6), 385-481 (2003)

11. Goswami, T., Das D.K., and Goswami, D., Controlling the femtosecond laser-driven transformation of dicyclopentadiene into cyclopentadiene. Chem. Phys. Lett. **558**, 1-7 (2013)
12. Ashkin, A., Dziedzic, J.M., Bjorkholm, J.E., and Chu, S., Observation of a single-beam gradient force optical trap for dielectric particles. Opt. Lett. **11**, 288-290 (1986)
13. Phillips, W.D., Laser cooling and Trapping Neutral Atoms. Rev. Mod. Phys. **70**, 721-741 (1998)
14. De, A.K. and Goswami, D., Towards controlling molecular motions in fluorescence microscopy and optical trapping: a spatiotemporal approach. Int. Rev. Phys. Chem. **30**(3), 275-299 (2011)
15. Mondal, D. and Goswami, D.,Controlling local temperature in water us-ing femtosecond optical tweezer. Biomed. Express **6**, 3190-3196 (2015)