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FEMTOSECOND LASERS

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ABSTRACT

Femtosecond laser which belong to the category of ultrafast lasers or ultra-short pulse lasers emit optical pulses with duration much below 1ps of the order of 10-15 sec. Mode locking lasers are used to produce such ultrashort pulses. Originated in 1963 when first laser was produced, now we have various kind of lasers with application in varied areas like material processing, imaging and spectroscopy, biomedical etc. The field of femtosecond laser has achieved significant advancement in interaction of laser with matter and material processing. The extreme short pulse wave can achieve very high intensity. Lasers have a wide application in industrial material processing. The phrase "laser micromachining" has been used to describe laser machining applications where feature sizes on the micrometer or tens of micrometers scale are achieved. Avalanche Ionization and Multiphoton Ionization are the two types of the non-linear processes. The problems in micromachining of difficult to machine materials (ceramics, silica etc.), graphitization in case of diamond, issue of melting in case of bulk materials are overcome by using femtosecond laser. It has applications in bio-medical field also. Femtosecond laser technology has recently been developed for using in cataract surgery. LASIK surgery is performed to reshape the eye's cornea for correction of myopia, hyperopia and astigmatism. As the technology is recent, still there is no proper nomenclature for femtosecond laser assisted cataract surgery (ReLACS, FLACS, FALCS, TLACS). Using FSLs, we can build a camera that is capable of recording at around a trillion fps. Potential applications include search and rescue planning in hazardous conditions, collision avoidance for cars, and robots in industrial environments. Transient imaging also has significant potential benefits in medical imaging that could allow endoscopes to view around obstacles inside the human body.

Keywods:- *Femto Second Laser, LASIK surgery, micro machining, Femto-Photography.*

I. INTRODUCTION- LASERS

LASER - light amplification by stimulated emission of radiation A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories.

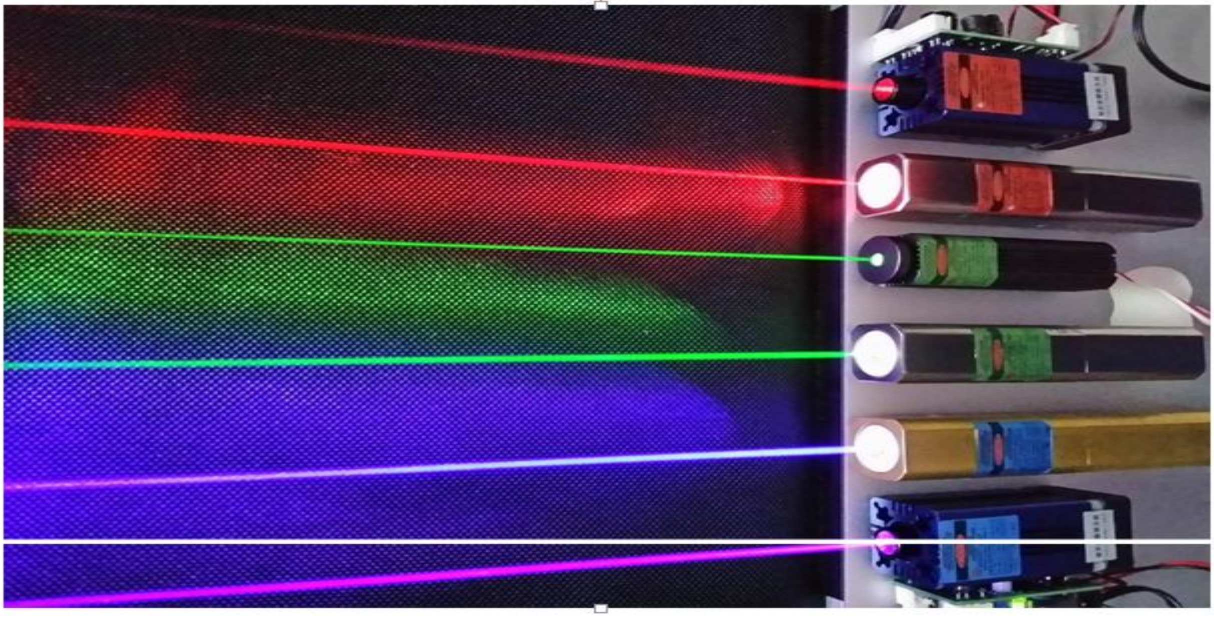

Figure 1:
Laser
(Courtesy: https://upload.wikimedia.org/wikipedia/commons/b/b9/LASER.jpg)

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II. FEMTOSECOND- LASERS

A femtosecond laser is a laser which emits optical pulses with a duration well below 1 ps (*ultrashort pulses*), i.e., in the domain of femtoseconds (1 fs = 10^{-15} s). It thus also belongs to the category of ultrafast lasers or ultrashort pulse lasers. The generation of such short pulses is nearly always achieved with the technique of passive mode locking.

Mode locking is a technique to generate ultrashort pulses laser. Laser resonator contains an active element or a non-linear passive element circulating in the laser resonator.
Passive mode locking involves much shorter ultrashort pulses because of a saturable absorber which is already driven by short pulses.

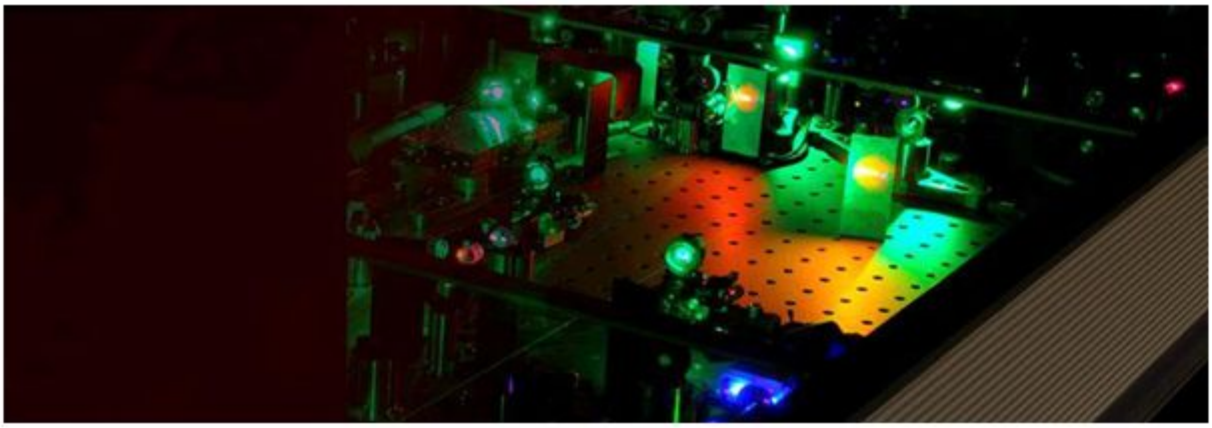

Figure 2: Femtosecond Lasers (Courtesy: http://img.directindustry.com/images_di/photo-g/63506-5254845.jpg)

III. ORIGIN

1963: Logan E. Hargrove, Richard L. Fork and M.A. Pollack report the first demonstration of a mode-locked laser; i.e., a helium-neon laser with an acousto- optic modulator. Mode locking is fundamental for laser communication and is the basis for femtosecond lasers.

1982: Peter F. Moulton of MIT's Lincoln Laboratory develops the titanium- sapphire laser, used to generate short pulses in the picosecond and femtosecond ranges

1994: femtosecond laser was used to ablate micrometre-sized features on silica and silver surfaces

May 7, 1996: Ronald Kurtz, Medical Student at University of Michigan examines a patient at W.K. Kellogg Eye Centre. The retinal surgery of the patient was accidentally caused by femtosecond lasers.

1998: First femtosecond laser prototypes for medical purposes were built in
Irvine, California

2000: first LASIK((laser-assisted in situ keratomileusis) procedures performed by Dr. David Schanzlin, Ron Kurtz, Imola Ratkay-Traub(Budapest)

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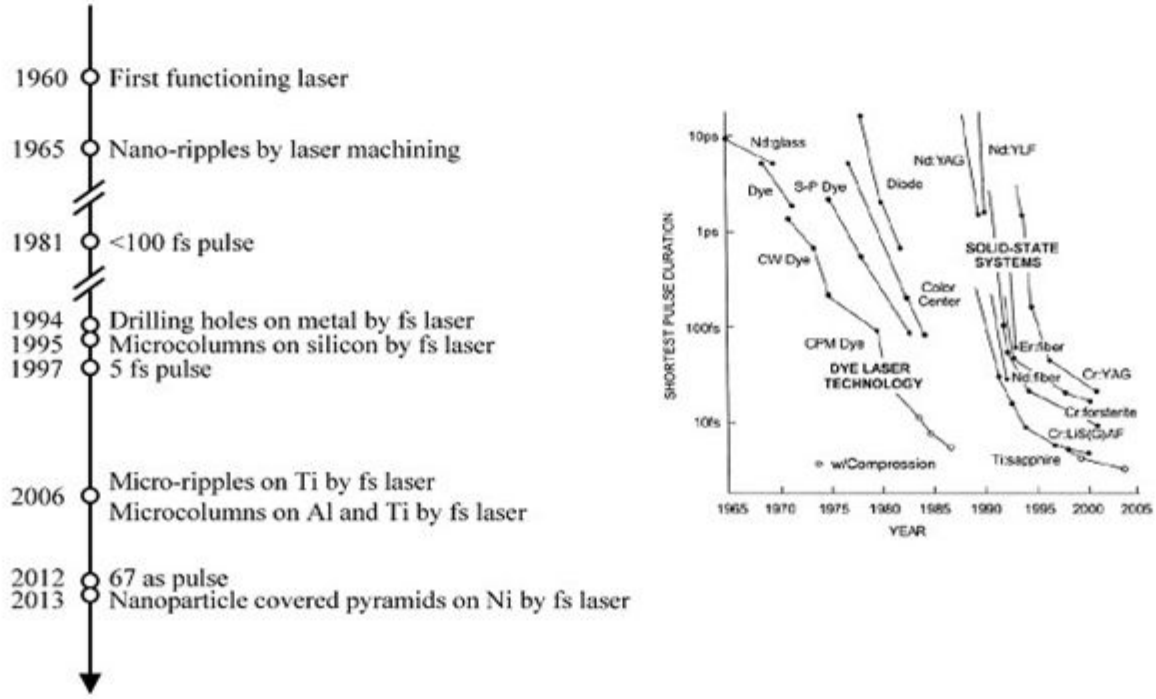

Figure 3: Origin of Femtosecond Lasers
(Courtesy: Page 55, Femtosecond Laser Development by Franz X. Kärtner1, Erich P. Ippen1 and Steven T. Cundiff, Research Laboratory of Electronics, Massachusetts Institute of Technology)

IV. TYPES OF FEMTOSECOND LASERS

Bulk Lasers

Bulk Lasers are high quality lasers with duration of ultrashort pulses ranging from 30fs to 30ps. Generally, ytterbium-doped operate in this regime with average output power between 100mW to 1W. Titanium– sapphire lasers with advanced dispersion compensation are even suitable for pulse durations below 10 fs, in extreme cases down to approximately5 fs. Repetition rate of pulse is kept between 50 MHz to 500 MHz. However, low repetition rate around few MHz with higher pulse energies is also possible.

Fibre lasers

Fibre lasers are passively mode locked lasers offering pulse duration between 50fs to 500fs. Average power of these lasers is few milliwatts with repetition rate of 10 MHz to 100 MHz. Combination with fibre amplifier can provide higher average powers and pulse energies. These lasers prove out to be fairly cost effective in mass production but may face various technical challenges for higher performance.

Dye Lasers

The field of femtosecond lasers or ultrashort pulses was dominate by Dye Lasers before the emergence of titanium–sapphire lasers. Pulse durations of the order of 10 fs. Different gain bandwidth allows different emissions at various wavelength. These lasers aren't in practise today because of their handling issues.

Semi-Conductor Lasers

These type of lasers are in trend due to the fact that external pulse compression may help to achieve much shorter pulse durations. These lasers can deliver a combination of short pulse durations, high pulse repetition rates, and high average output power. However, they are not suitable high pulse energies.

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Other types
Color center lasers and free electron lasers are the most exotic types. Free electron lasers can be made to emit femtosecond pulses in the form of X- rays.

V. APPLICATION AREAS

1. Material Processing
a. Micromachining very fine features b. Direct laser Writing
c. In-Volume Selective Laser Etching
d. Glass Welding
e. Sapphire Dicing and Scribing f. Sub-Surface Marking
g. Surface Texturing
h. Processing Transparent Materials i. Two-Photon Polymerization
j. Medical Device Manufacturing k. Nanoparticle Generation
l. Pulsed laser Deposition

2. Biomedical
a. Cancer Detection
b. Cell Transfection and Photoporation c. Collagen Imaging
d. Multiphoton Microscopy e. Neuroscience
f. Microsurgery
g. Cataract Surgery
h. Refractive Vision Correction i. Tissue Welding

3. Imaging and Spectroscopy a. Multiphoton Microscopy
b. Laser-Induced Breakdown Spectroscopy c. Pump-Probe Spectroscopy
d. Second/Third Harmonic Generation Imaging e. Terahertz generation and detection
f. Ultrafast Metrology g. Femtophotography

VI. FEMTOSECOND LASER MICROMACHINING

Ultrafast laser micromachining is significantly different from ordinary laser machining techniques where waves are either continuous or pulsed at the rate of microsecond.

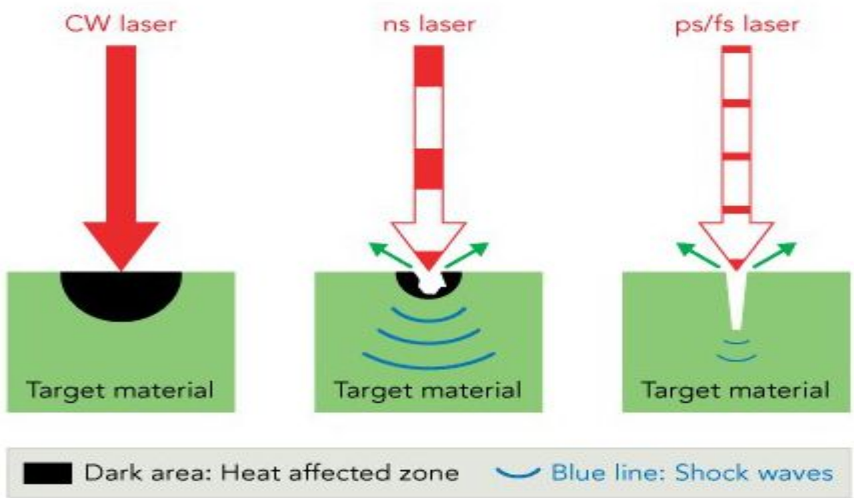

Figure 4: Laser Material Interaction basic for different types of lasers
(Courtesy: http://www.industrial-lasers.com/articles/2012/06/femtosecond-laser-micromachining-a-back-to-basics-primer.html)

On the above figure, the difference between a continuous wave laser, a nanosecond laser and a femtosecond laser is shown. The blue lines signify shock waves and the black region denotes Heat Affected Zone. The continuous waves removes material primarily by melting. Due to melting, a large amount of heat affected zone is created. The

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nanosecond laser in the centre leaves relatively smaller heat affected zone but the work material is affected by shock waves. The melt is removed via vapour pressure and recoil pressure. In femtosecond laser machining, the duration is very small as compared to the time required for energy transfer between atoms. As a result, high pressure and temperature is generated and material is removed directly to the vapour phase without any recast layer and hence there is no rough surface formation.
The field of femtosecond laser has achieved significant advancement in interaction of laser with matter and material processing. The extreme short pulse wave can achieve very high intensity. For example, a laser pulse with a pulse width of 100 fs (10 s) and a pulse energy of only one-third of 1 mJ has a peak intensity of 10 W/cm when focused to a 20-µm diameter spot. A 10-ns-long laser pulse would have to have 100 J in the pulse to reach the same intensity.

Lasers have a wide application in industrial material processing like cutting, welding, ablating, drilling and other modifications of the material. The phrase “laser micromachining” has been used to describe laser machining applications where feature sizes on the micrometre or tens of micrometres scale are achieved.

The first step is the absorption of laser by the work piece in laser micromachining. This is accomplished either by linear or non-linear processes. The focused region is heated to vaporization temperature depending upon the intensity of laser.

The second step is laser induced breakdown. The material is transformed into an absorbing plasma by the laser pulse. Subsequent plasma causes heating that leads to irreversible changes in the host.

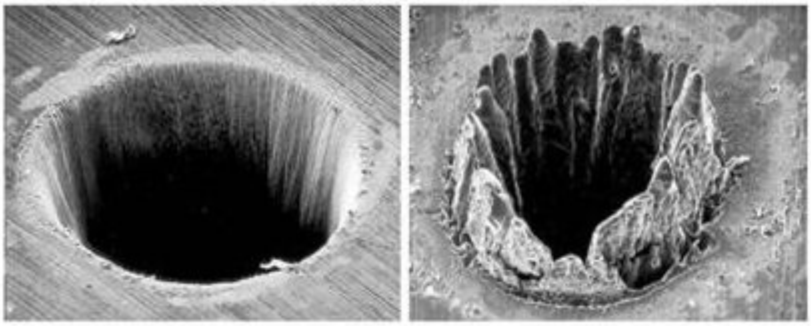

Figure 5: Femtosecond Laser vs Nanosecond laser
(Courtesy: https://www.semrock.com/Data/Sites/1/semrockimages/technote_images/fio-wp-figure-10.jpg)

There are two types of non-linear processes
i. Avalanche Ionization
ii. Multiphoton Ionization

Avalanche Ionization
In a transparent dielectric material, the energy of laser photon is less than the ionization potential. As a result, they don’t absorb these photon. However, there are some free electrons present in every material due to several factors. The free electron doesn’t gain energy when simply wiggling in the laser field. Although, the free electron can absorb energy when it collides with bound electron. In this way next collision will result in multiple free electrons. When enough bound electrons are ionized by this avalanche process, a plasma with a “critical density” is created, and the transparent material is broken down and becomes absorbing.

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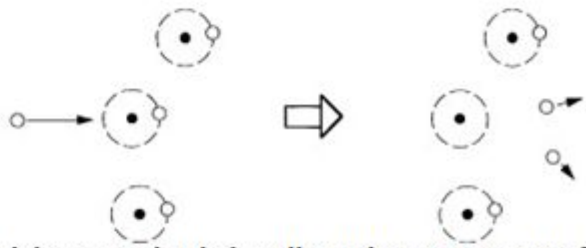

Figure 6: Schematic of electron avalanche by collisional impact ionization. Secondary free electrons are generated during collisions with electrons whose kinetic energy is greater than the bound electrons binding energy
(Courtesy: Laser Ablation and Micromachining with Ultrashort Laser Pulses, Volume 33 of IEEE Journal of Quantum Electronics)

Multiphoton Ionization

When the intensity of laser is high enough, the bound electrons can be directly ionized. The multiphoton ionization is significant in ultrashort pulses and not on continuous waves.

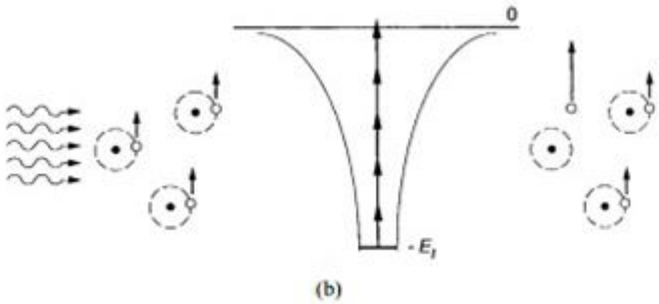

Figure 7: The multiphoton ionization process. The bound electron is ionized by simultaneously absorbing m pho tons
(Courtesy: Laser Ablation and Micromachining with Ultrashort Laser Pulses, Volume 33 of IEEE Journal of Quantum Electronics)

Micromachining on Metals

The micromachining of bulk metals was a tedious job because of issue of melting but femtosecond lasers overcame this problem. The neodymium vanadate (Nd:YVO4) lasers have short pulse duration and repetition rate of few tens of kilohertz brought robustness to the process. Metals such as stainless steel can also be micro-machined with ease.

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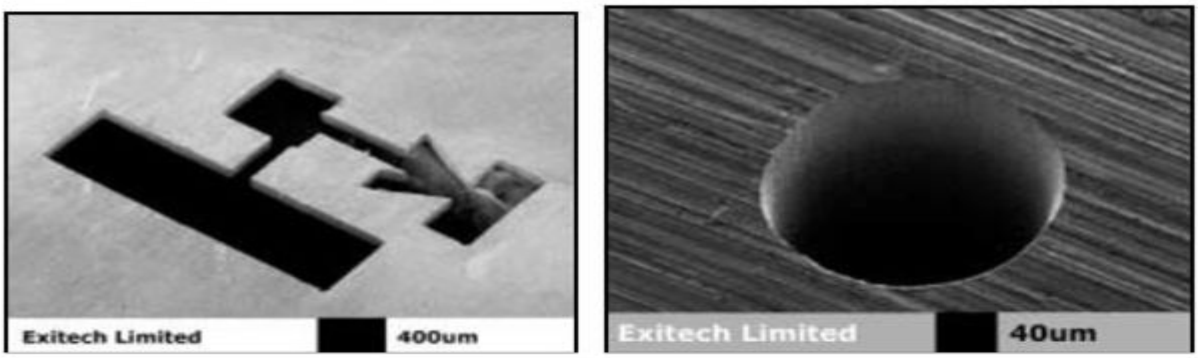

Figure 8: Femtosecond laser micromachining of aluminium (left) and steel (right)
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

Micromachining on Glass
The use of glass in the biomedical industry and MEMS devices has led to increasing attention toward glass micromachining.

ass micromachining.

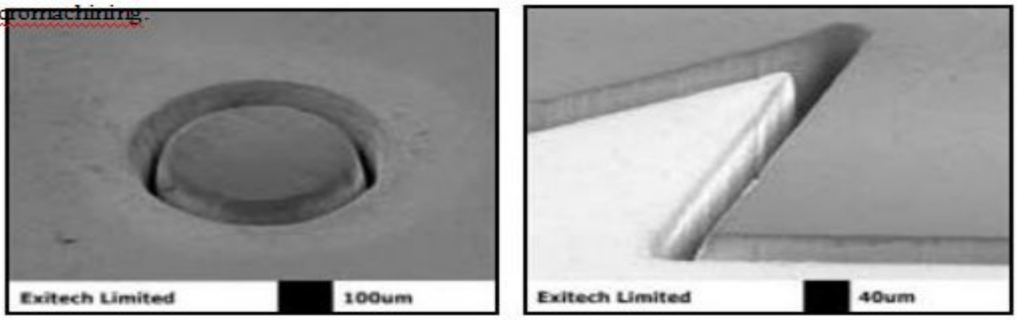

Figure 9: Glass samples micro machined using a femtosecond laser
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

Micromachining on Diamond

Diamond has a very wide application in this field due to its inertness and hardness. Synthetic CVD processes has brought a lot of attention towards diamond for use in detectors, optical applications, sensors etc. However, one of the drawback of its inertness and hardness is that it is very difficult to machine conventionally. Lasers have overcome this problem, especially IR Nd:YAG is
used to machine diamond.

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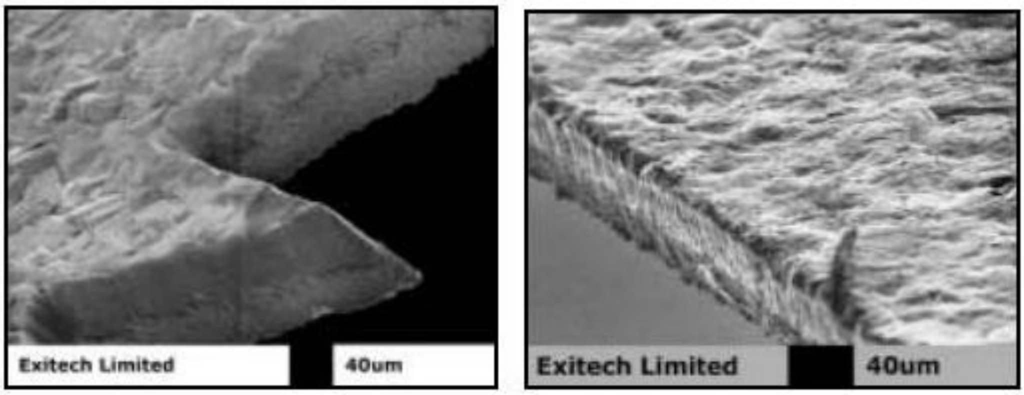

Figure 10: (a) Cutting of a CVD diamond wafer using a femtosecond laser, (b) sample of CVD diamond where the surface has been smoothed using a femtosecond laser and the edge has been cut using a nanosecond pulse 355nm Nd:YVO4 laser.
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

Diamond has various application in the field of detectors and sensors. However, these devices require very smooth surface. To achieve proper deposition and contacts on the surface, the metal electrodes need a smoother surface than is present with the as grown substrate. Conventional process no longer meet the requirements as they tend to graphitise diamond. Laser smoothing can be used to remove the irregularities from the surface as shown in figure 10(b). The problem of graphitisation is tackled with the help of femtosecond lasers.

Micromachining of Silica

Silicon has gained a tremendous boost in the field of semiconductor industry. However, due to adsorption property of silicon, it is difficult to machine silica with conventional processes. Femtosecond lasers have been used to machine silica as shown in figure 11.

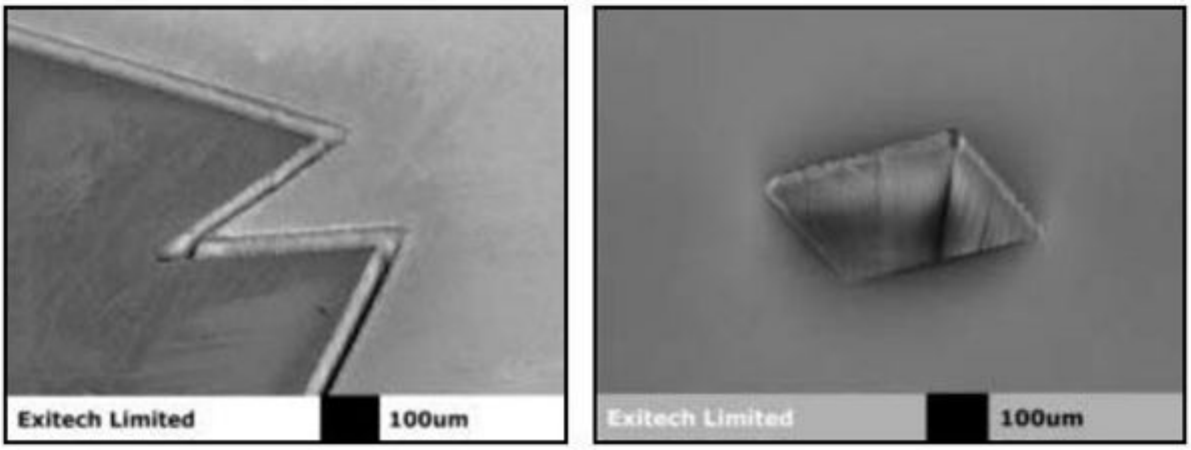

Figure 11: Samples of silica micro machined using a femtosecond laser.
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

Micromachining of Ceramics

Ceramics such as zirconia and aluminium carbide are widely used in the MEMS devices. Thermal influence is a crucial factor during conventional machining. To overcome this problem, femtosecond lasers are used as show in figure 12.

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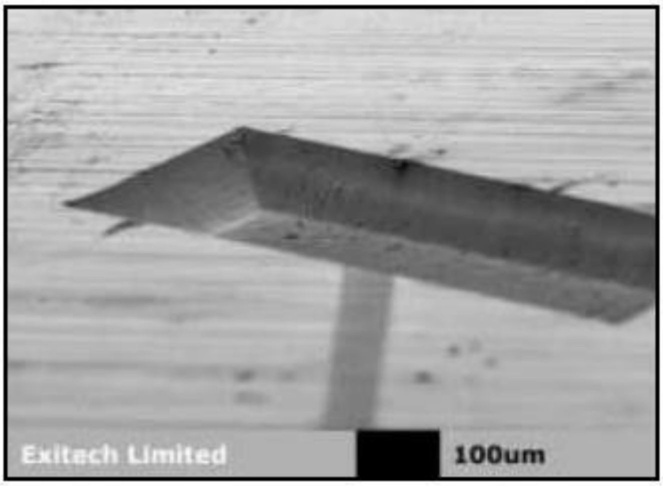

Figure 12: A micro cavity machined into zirconia using a femtosecond laser.
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

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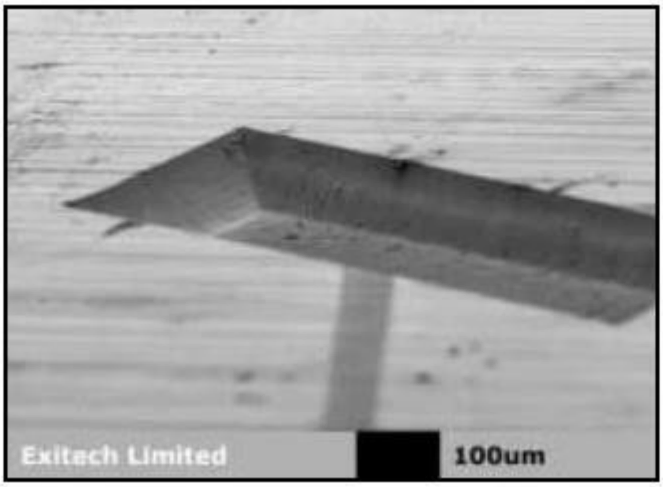

Figure 12: A micro cavity machined into zirconia using a femtosecond laser.
(Courtesy: Femtosecond Laser Micromachining: Current Status and Applications by Nadeem H. Rizvi, Oxford, UK)

VII. FEMTOSECOND LASER: CATARACT SURGERY

Cataract also called cloudy lens is an especially common eye abnormality that occurs mainly in older people. A cataract is a cloudy or opaque area(s) in the lens which results in poor vision. The transparency of human eye lens is ensured by the protein fibers in it. With age, denaturation of these protein fibers takes place which results in the formation of cloudy substance. Due to this the transparent nature of lens is lost and should be surgically replaced with an artificial lens to restore proper vision.

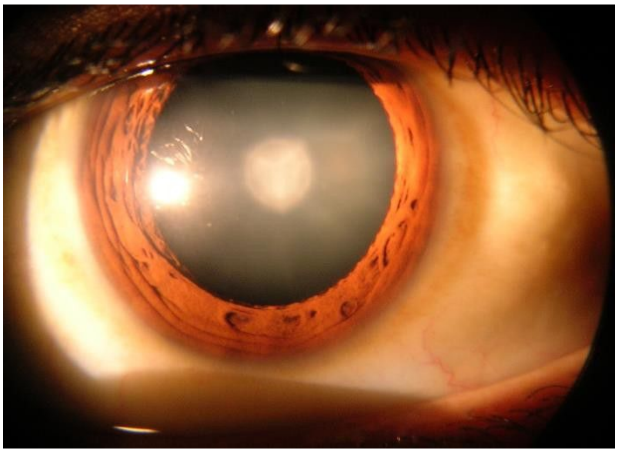

Figure 13: Magnified view of a cataract seen on examination with a slit lamp (Courtesy:https://upload.wikimedia.org/wikipedia/commons/thumb/b/ba/Cataract_in_human_eye.png/800px- Cataract_in_human_eye.png

Femtosecond laser technology has recently been developed for using in cataract surgery. Initially it has been introduced clinically in 2001 as a new technique for creating lamellar flaps in LASIK (Laser in situ Keratomileusis). LASIK provides a permanent alternative to eyeglasses or contact lenses. LASIK surgery is performed to reshape the eye's cornea for correction of myopia, hyperopia and astigmatism. Once the eye is immobilized, a flap is created with a mechanical microkeratome (precision surgical instrument) using a femtosecond laser. The femtosecond laser creates a series of tiny closely arranged bubbles within cornea. A hinge is left at one end of this flap and is folded back revealing the middle section of cornea for surgery. Femtosecond laser technology use photo-dissection to create side cuts for LASIK flaps in cornea.

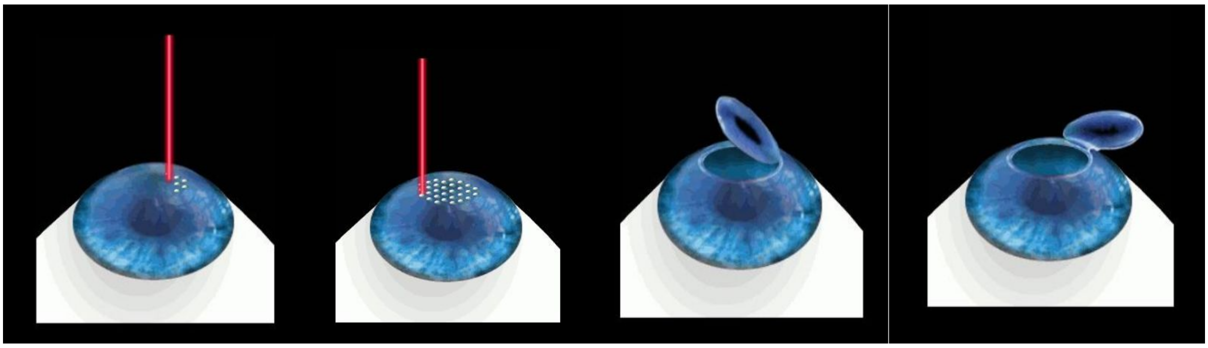

Figure 14: Flap creation with femtosecond laser
Courtesy: https://upload.wikimedia.org/wikipedia/commons/4/43/Lasik_Femtosegundo.gif)

As the technology is recent, still there is no proper nomenclature for femtosecond laser assisted cataract surgery. The more common used names include Refractive laser-assisted cataract surgery (ReLACS), Femtosecond laser-assisted cataract surgery (FLACS), Femtosecond-assisted laser cataract surgery (FALCS), Therapeutic laser-assisted cataract surgery (TLACS). With the development of new technology of femtosecond laser-assisted cataract surgery, challenges like benefits Vs finance of the equipment and logistics of employing this system into clinical practice.

Femtosecond Laser Technology:

Femtosecond laser technology systems use neodymium: glass 1053nm (near- infrared) wavelength light. Due to this the light can be focused at a 3 µm spot size. The important feature of femtosecond laser is the speed at which the light is fired and focused ultrashort pulses (order of femto sec). This eliminates the collateral damage of surrounding tissues and the heat generation associated.

Photodisruption: The energy from laser is absorbed by the tissue and plasma formation of free electrons and ionized molecules takes place. This then expands, creating cavitation bubbles which enlarge and coalesce to dissect tissue on a microscopic scale. This conversion of laser energy into mechanical energy is called Photodisruption.

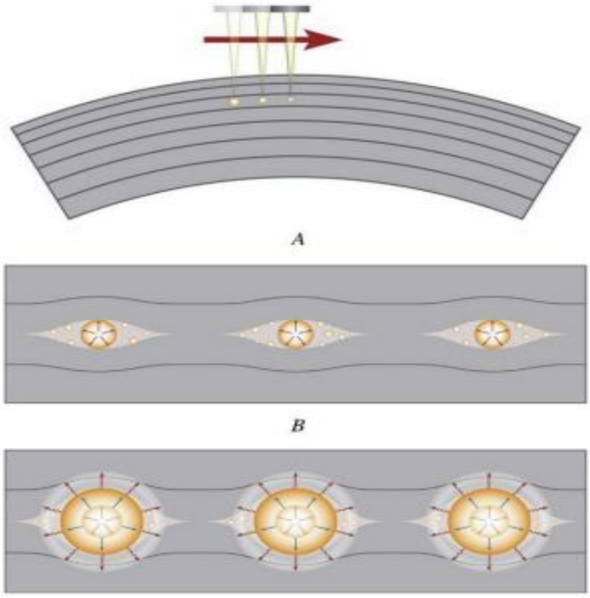

Figure 15: Highly focused femtosecond laser pulses create plasma that rapidly expands in a cavitation bubble, separating target tissue. A: Highly focused femtosecond laser pulses. B: Formation of cavitation bubbles. C: Cavitation bubbles enlarge and coalesce to allow separation of tissue (Courtesy: Femtosecond Laser Cataract Surgery: J. cataract refractive surgery, Volume 39, November 2013)

Parameters can be set so that neighboring shots can be closer enough for overlap of later formed cavitation bubbles or far for impartial overlap. Closer shots eliminate tissue bridges whereas in other case they should be bluntly dissected afterwards.

Procedure:

Docking: Docking involves the position of the patient. The patient should be flat with minimal neck support. The head should be restricted with a tilt so that the operated eye will be in a higher plane to clear nose and to facilitate proper applanation. Applanation is the flattening of cornea by application of pressure. Proper docking should ensure that the patient remain still for accurate imaging and application of laser for surgery.

Patient-Interface system: The patient-interface systems can be classified into two types, contact (applanating) and non-contact (non-applanating). Contact systems have smaller diameter and can fit it smaller orbits whereas non-contact systems don't apply much pressure and thus leads to lesser increase in Intra- ocular pressure (IOP). Contact systems cause more increase in IOP which causes internal blood leakage. Also non-contact systems offer wider field of view. Rapid

evolution of interface systems is taking place with new designs aimed at providing better, safe and reproducible results.

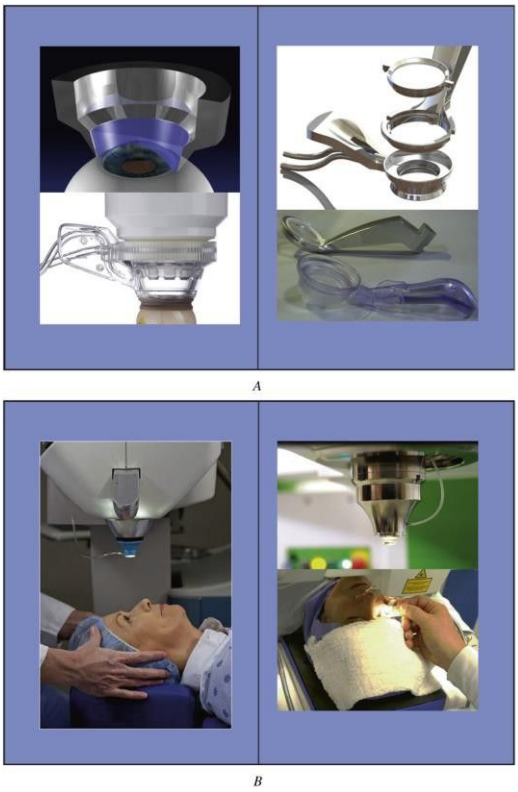

Figure 16: Four Patient-interface designs
A: Non-applanating B: Applanating
(Courtesy: Textbook of Refractive Laser Assisted Cataract Surgery (ReLACS). Newyork, Springer, 2013 vii-viii)

Imaging: Femtosecond laser systems uses spectral-domain optical coherence tomography (OCT) or 3-D confocal structural illumination (3-D CSI) to image and plan the treatment. Cornea should be centered within the applanated area for proper positioning of incisions and for proper centering in Capsulorhexis. Capsulorhexis is a technique used to remove the lens capsule during cataract surgery. This centering is very much crucial for positioning of Intra-ocular lens (IOL) especially in case astigmatic patients. To get quality image and proper laser application cornea must be clear of any scarring or folds. While docking with contact applanation, care should be taken to remove corneal folds. In systems with air-fluid interface there should not be any bubbles. The applanating lens should be clear and the patient should remain still while the image is being captured.

Laser treatment: The time taken for laser treatment depends on laser platform used and degree of lens softening chosen by the surgeon. It can last from 30 seconds to 3 minutes. During laser treatment there is a mild increase in IOP which may cause circumferential subconjunctival hemorrhage. This will be resolved in a couple of days. Suction in femtosecond laser assisted cataract surgery is less compared to in femtosecond LASIK surgery.The first part of the treatment is capsulorhexis which takes 1.5 to 18 seconds. Capsulorhexis is followed by lens fragmentation and finally corneal wound creation. Capsulorhexis also known as continuous curvilinear capsulorhexis (CCC) is a techinique used to remove anterior lens capsule during cataract surgery by means of shear and stretch forces. Unlike other steps where if suction is lost, it can be reapplied through suction ring, in capsulorhexis if suction is lost the process should be completed manually.

Based on the segmentation pattern selected by the surgeon, lens fragmentation is done next. Depending on the degree of lens softening chosen the laser time may vary between 30 to 60 seconds. Segmentation pattern and lens softening are chosen depending on the grade of lens. Finally clear corneal wound is created. After the completion of laser treatment suction is released, patient interface is removed and the patient is slowly undocked from the laser. After laser treatment, phacoemulsification takes place. It is recommended that phacoemulsification should occur within 30 to 40 minutes after femtosecond laser treatment.

Phacoemulsification is a cataract surgery in which eye's internal lens is emulsified with an ultrasonic hand piece and aspirated from the eye. The phaco probe is an ultrasonic hand piece with a titanium or steel needle which is vibrated with an ultrasonic frequency. Due to this vibration the cataract gets emulsified and the pump aspirates particles through the tip.

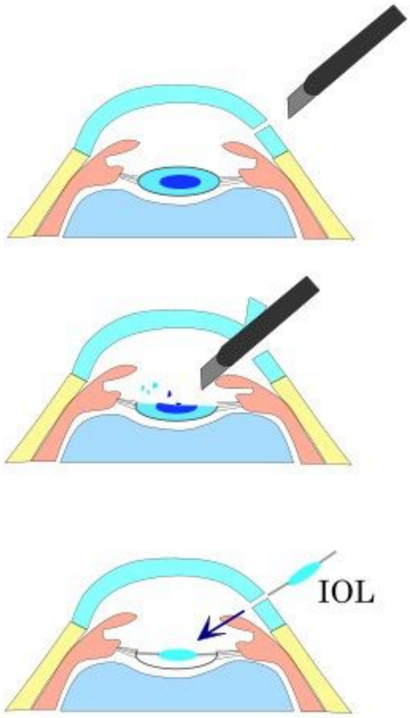

Figure 17: Phacoemulsification and replacement with intraocular lens
(Courtesy: https://upload.wikimedia.org/wikipedia/commons/thumb/2/2e/PEA_and_IOL.svg/744px-PEA_and_IOL.svg.png

Complications and challenging cases:

Orbit, Neck and Back issues
Small pupils
Suction loss
Radial tear after lens capsule incision
Computer issues

Outcomes:

CCC created with femtosecond laser results are more stable compared to manual.
Lens capsule incisions created with femtosecond laser are more precise, stable and reproducible.
With the use of femtosecond laser less energy is expended inside the eye.
After lens fragmentation using femtosecond laser the time required for phacoemulsification is decreased considerably.
Good visual and optical quality outcomes have been reported.

Summary:

Femtosecond laser assisted cataract surgery presents a new set of clinical and financial challenges to the cataract surgeon. This technology added cost to cataract surgery which will be ultimately paid by patient. It seems to be a safe, efficient and reproducible procedure. Further studies will demonstrate the potential benefits of this emerging technology. We are only beginning to comprehend the benefits and complexities of this new technology.

VIII. FEMTO-PHOTOGRAPHY AND LOOKING AROUND CORNERS

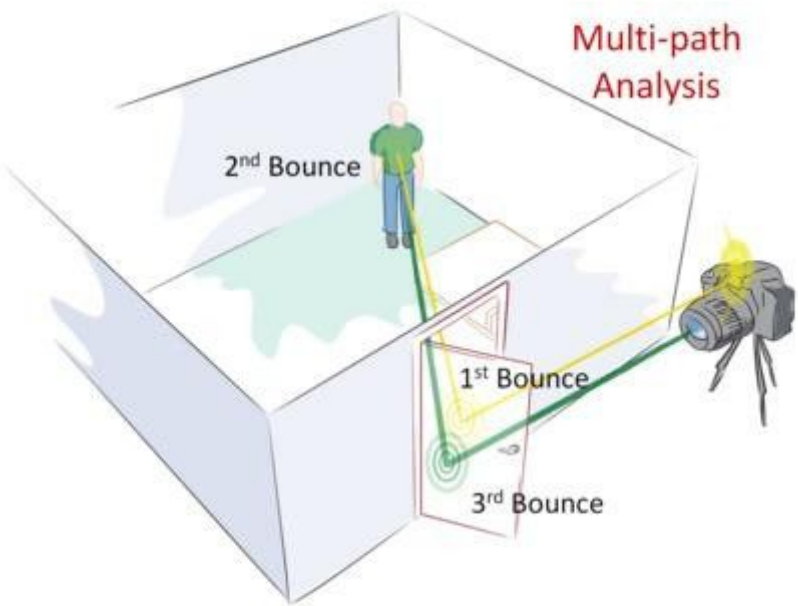

Figure 18: Figure 1 Looking Around Corners. Courtesy: http://web.media.mit.edu/~raskar/cornar/

Using FSLs, we can build a camera that is capable of recording at around a trillion fps. Also, the device makes it possible to record transient images and has applications of looking around corners.

The FSL is used to generate an ultra- short pulse of light that acts like a flash of light to illuminate the objects in the scene. This laser flash lasts only about one trillionth of a second. The light reflected off the objects is collected by a camera at close to one trillion fps and this makes such high speed photography possible. In a typical camera with higher exposure times, the light that bounces off the objects is collected on the sensor and is averaged over the duration of time for which the shutter is open. Due to this averaging, the temporal information of the reflected light coming to the camera is list for that duration of time. But with a camera that is capable to recording at femto second exposure times, the temporal component can be kept intact.

By sequentially illuminating the object by periodic femto-pulses of light and by careful triggering of the camera to take pictures at specific instants in time, we can record a scene at around a trillion fps. The camera is set to have a recording frequency of just slightly more than the frequency of the light pulses sent by the FSL flash. As such, the camera is able to record in each frame a slightly different position of the light wave going through the object. The images so collected are then processed by powerful software and stitched into a complete movie of the event happening in extreme slow motion. Due to the nature of the imaging process, only events that are perfectly repeatable are possible to be recorded.

For recording of objects that are off the line of sight, a slightly different technique is used. With the high temporal resolution available from the above methods, we are now able to exploit the fact that light travels at a finite speed.

An ultra -short pulse is shown on the reflector from which the light reflects to the scene to be visualised (that lies off the line of sight). Now as this light packet travels through and scans through the scene, it is reflected back by the objects in the scene. Some of this reflected light reaches the reflector and is reflected back to the camera. Now, with due to the fact that light takes longer to reflect back from farther objects, the difference in the time of the light intensities that are received at the camera can be formulated as a measure of the depth in the scene. This principle of photography is called transient imaging. We are imaging the light coming from the scene in a complete temporal resolution and are not averaging out the light for the duration of the exposure time.

Also, a light photon that is reflected once from the scene and is obtained at the receptor has a higher intensity (and smaller time of flight) than a photon that has undergone multiple bounces. This difference in intensity also acts as a measure of another depth dimension the scene (Fig.2).

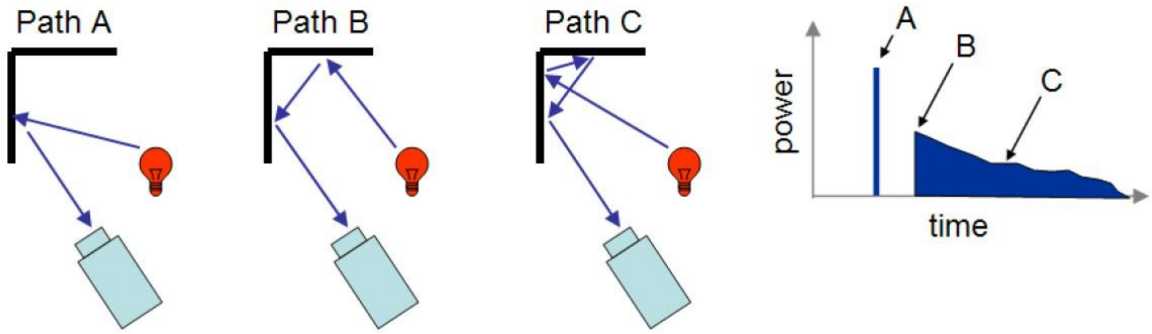

Figure 19: Light transport that proceeds along different scene paths takes different amounts of time to reach the camera. Traditional cameras integrate all of this light into a single pixel value. The transient photometric response function captured by a time camera (shown here for a single pixel), allows these paths to be sampled separately, leading to additional scene understanding.
Courtesy: %D time-light transport matrix, R. Raskar, D Davies.

Obtaining these photographic frames and processing those using concepts of light path calculation and inverse geometry techniques, one can obtain a reconstruction of the scene that is off light on sight up-to centimetre level precisions.

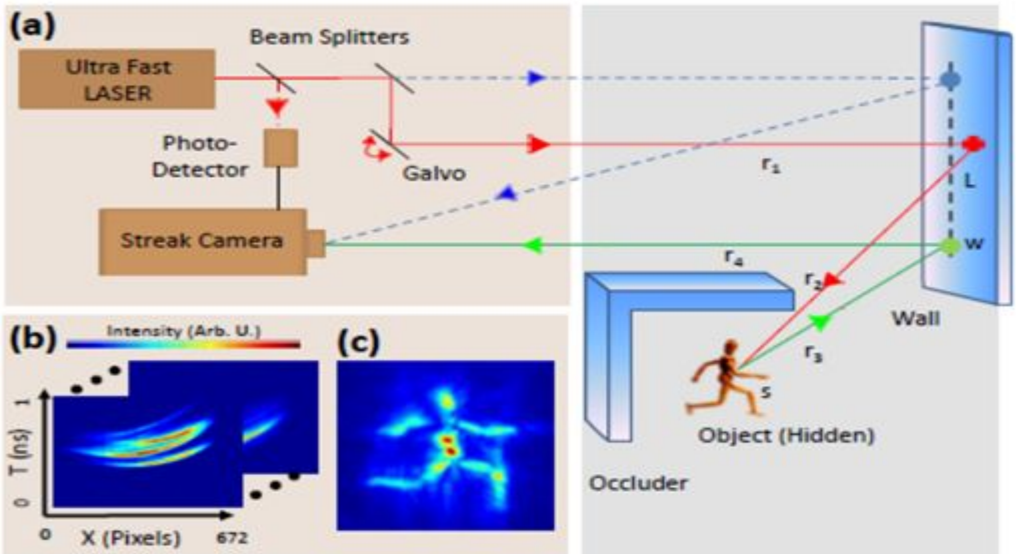

Figure 20 (a) the Capture Process. (b) An example of streak images taken. (c) The projected view of the 3D reconstruction
Courtesy:
http://www.laserfocusworld.com/content/dam/lfw/print-articles/2012/12/1212LFW_fea3_fig1.jpg

It is important to make sure that all the light that is received at whatever times at the receptor must have originated from the same packet of light. This is what makes the flash pulse to be ultra-short. Otherwise, the light from one part of the pulse duration can interact with light from the other part of the pulse. The two photons can travel different paths, have different number of bounces and arrive at the receptor at the same time, thus interfering and destroying the informati mon frothe intensity duration diagrams.

Potential applications include search and rescue planning in hazardous conditions, collision avoidance for cars, and robots in industrial environments. Transient imaging also has significant potential benefits in medical imaging that could allow endoscopes to view around obstacles inside the human body.

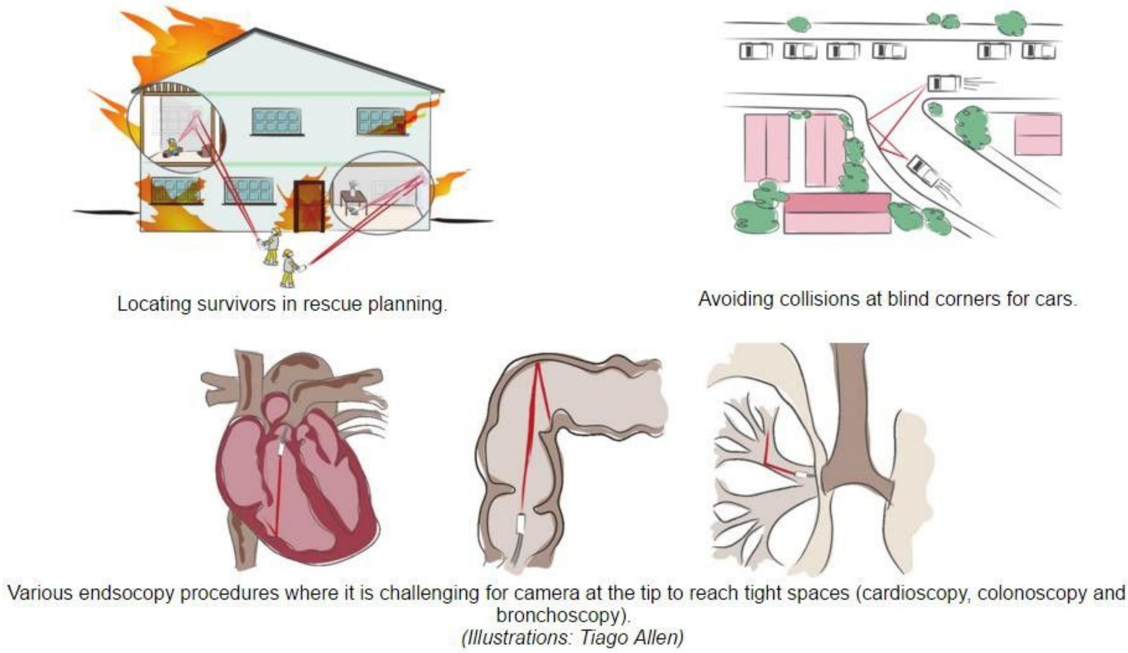

Figure 21 Applications of Femto Photography
Courtesy:
http://web.media.mit.edu/~raskar/cornar/

The challenges involved in these techniques primarily consist of the lack of robust mathematical theory for the inversion of the images to obtain the 3D reconstructions. For complex geometries in the scene, the number of possible reflection paths that the light can take grow exponentially with the scene complexity. It becomes correspondingly difficult to solve the inverse geometry problem.

Another limitation is that imaging of only those events that are repeatable in time is possible.

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