Femtosecond Lasers and its Application in Medical Sciences

Project Report

Submitted in complete fulfilment of the requirements for the award of the degree of

Bachelor of Technology

in

Software Engineering

Submitted by:

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DECLARATION

We (Ayush Jaiswal- 2K20/B8/21 and Nitesh Kumar- 2K20/B8/21) hereby certify that the work which is presented by us in the project on the topic "**Femtosecond Lasers"** in fulfilment of the requirement for the award of the Degree of Bachelor of Technology in Software Engineering and submitted to the **Department of Applied Physics**, Delhi Technological University, Delhi is a record of our own, carried out under the supervision of **Dr. Renuka Bokolia.**

Whenever we have used materials (data, theoretical analysis, and text) from other sources, we have given due credit to them in the text of the report and giving their details in the references.

Ayush Jaiswal **Nitesh Kumar**

2K20/B8/21 **2K20/B8/70**

Supervisor Certificate

To the best of my knowledge, the report consists of the work of analysing the contents through secondary sources, and the work has not been submitted to any other Institution for any other degree in this university or any other University of India or abroad.

Place: Delhi

Date: **Supervisor Name and Signature**

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ABSTRACT

Laser, a device that stimulates atoms or molecules to emit light at particular wavelengths and amplifies that light, typically producing a very narrow beam of radiation. The emission generally covers an extremely limited range of visible, infrared, or ultraviolet wavelengths. Many different types of lasers have been developed, with highly varied characteristics. Laser is an acronym for **"light amplification by the stimulated emission of radiation."**

A **Femtosecond Laser** (FSL) is a laser which emits optical pulses with a duration of 1 ps (ultrashort pulses), i.e., within the domain of femtoseconds (1 fs = 10^{-15} s). It thus also belongs to the category of ultrafast lasers or ultrashort pulse lasers (which also include picosecond lasers). The application of FSL in ophthalmic surgery was first introduced in 2001. Since then, it's been increasingly utilized in anterior segment surgery. Femtosecond Laser Assisted Cataract Surgery (FLACS) provides the newest innovation in field of ophthalmology that has revolutionized the way cataract surgery is performed with potential of better outcomes and safety. Modern cataract surgery is fast becoming a refractive surgical procedure. Femtosecond laser assisted cataract surgery has been commercially available since 2011 and has revolutionized the way cataract surgery is performed across the world.

Despite the excellent results obtained with the current technology, perfection is demanded by patients and surgeons alike. Existing procedures, although safe and efficient, are considered to depend greatly on the skill and experience of the surgeon. This project would describe the technology available, discuss the potential benefits and challenges involved, and newer developments in this exciting new treatment modality.

Acknowledgement

In performing our case study based Innovative project, we had to take the help and guideline of some respected persons, who deserve our greatest gratitude. The completion of this assignment gives us much pleasure. We would like to show our gratitude to Dr. Renuka Bokolia, Supervisor for our Innovative Project. Giving us a good guideline for report throughout numerous consultations. We would also like to extend our deepest gratitude to all those who have directly and indirectly guided us in writing this assignment.

Many people, especially Ms. Priya Pradeep Kumar and Mr. Mrityunjay Kumar Singh, our classmates and team members itself, have made valuable comment suggestions on this proposal which gave us an inspiration to improve our assignment. We thank all the people for their help directly and indirectly to complete our assignment.

In addition, we would like to thank The Department of Applied Physics, Delhi Technological University for giving us the opportunity to work on this topic.

CONTENTS

INTRODUCTION

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation".** A laser differs from other sources of light in that it emits light which is coherent.

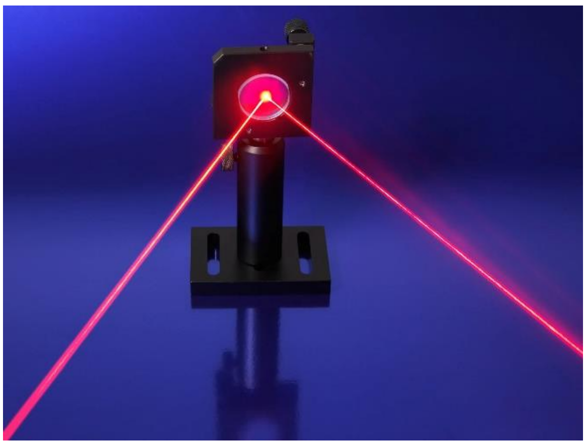
Lasers are used in optical disk drives, laser printers, barcode scanners, DNA sequencing instruments, fibre-optic, semiconducting chip manufacturing (photolithography), and free-space optical communication, laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in laser lighting displays for entertainment.

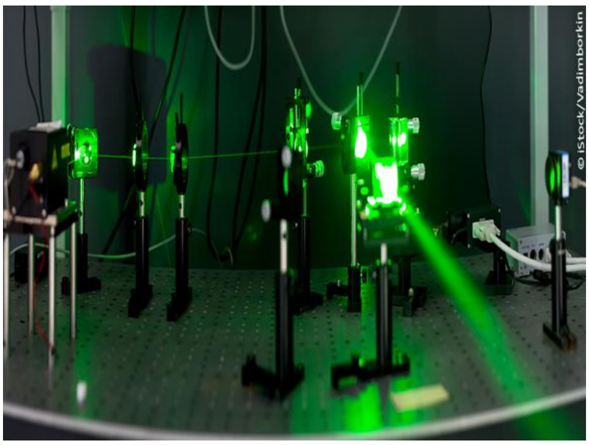
A laser oscillator usually comprises an optical resonator (laser resonator, laser cavity) in which light can circulate (e.g., between two mirrors), and within this resonator a gain medium (e.g. a laser crystal), which serves to amplify the light. Without the gain medium, the circulating light would become weaker and weaker in each resonator round trip, because it experiences some losses, e.g., upon reflection at mirrors. However, the gain medium can amplify the circulating light, thus compensating the losses if the gain is high enough. The gain medium requires some external supply of energy – it needs to be “pumped”, e.g., by injecting light.

The principle of laser amplification is stimulated emission.

Types of Lasers:

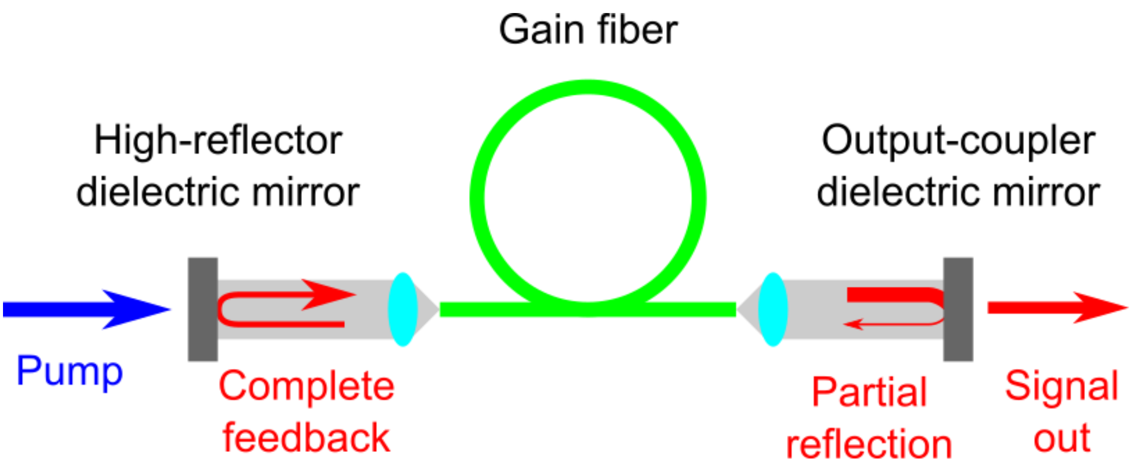
- **Semiconductor lasers**
- **Solid State Lasers**
- **Fiber Lasers**
- **Gas Lasers**





FIBER LASERS:

Fiber lasers are one class of solid-state lasers in which the gain medium is an **optical fiber**. Fiber lasers have been a key technology in the area of solid-state lasers, since the first proposal of using an optical fiber as a mode selector for lasers. An advantage of fiber lasers over other types of lasers is that the laser light is both generated and delivered by an inherently flexible medium, which allows easier delivery to the focusing location and target. This can be important for laser cutting, welding, and folding of metals and polymers. Another advantage is high output power compared to other types of laser. Fiber lasers are compact compared to solid-state or gas lasers of comparable power, because the fiber can be bent and coiled, except in the case of thicker rod-type designs, to save space. They have lower cost of ownership. Fiber lasers are reliable and exhibit high temperature and vibrational stability and extended lifetime.



Stimulated emissions from the gain fiber coherently amplify the signal as the signal repeatedly bounces back between the two signal reflectors. The reflector on one end of the cavity is a high reflector (ideally 100% reflectivity at the signal wavelength) in order to maximize the signal feedback to the cavity. The reflector on the other end of the cavity is a partial reflector (also called an output coupler) for extracting the signal out of the cavity, as well as providing the signal feedback to the cavity.

The output from a fiber laser can be either continuous wave (CW) or pulsed. Pulsed fiber lasers are created by modulating the loss of the laser cavity, and the pulse width is determined by the temporal profile of the loss modulation and the chromatic dispersion of the cavity.

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 (which also include picosecond lasers).

The generation of such short (sub-picosecond) light pulses is nearly always achieved with the technique of passive mode locking. That leads to pulses with moderate pulse energies (often in the nanojoule region) and high pulse repetition rates in the megahertz or gigahertz region. Far higher pulse energies (at lower repetition rates) are possible by using some kind of optical amplifiers system (*ultrafast amplifiers*) in addition to a femtosecond laser.

Femtosecond (FS) laser is an infrared laser with a wavelength of 1053nm. FS laser like Nd: YAG laser works by producing photo disruption or photoionization of the optically transparent tissue such as the cornea.

Usually the attribute 'ultrashort' applies to pulses with a temporal duration of a few tens of femtoseconds, but in a larger sense any pulse which lasts less than a few picoseconds can be considered ultrashort. The distinction between "Ultrashort" and "Ultrafast" is necessary as the speed at which the pulse propagates is a function of the index of refraction of the medium through which it travels, whereas "Ultrashort" refers to the temporal width of the pulse wave packet.

Types of Femtosecond Lasers:

Solid-state Bulk Lasers –

Passively mode-locked solid-state bulk lasers can emit high-quality ultrashort pulses with typical durations between 30 fs and 30 ps. Various diode-pumped lasers, e.g. based on neodymium-doped or ytterbium-doped gain media, operate in this regime, with typical average output powers between ≈ 100 mW and 1 W. Titanium–sapphire lasers with advanced dispersion compensation are suitable for particularly short pulse durations below 10 fs, in extreme cases down to approximately 5 fs.

The pulse repetition rate is in most cases between 50 MHz and 500 MHz, even though there are low repetition rate versions with a few megahertz for higher pulse energies, and also miniature lasers with tens of gigahertz.

Fiber Lasers

Various types of ultrafast fiber lasers, which are also in most cases passively mode-locked, typically offer pulse durations between 50 and 500 fs, repetition rates between 10 and 100 MHz, and average powers of a few milliwatts. Substantially higher average powers and pulse energies are possible, e.g. with stretched-pulse fiber lasers or with similariton lasers, or in combination with a fiber amplifier.

All-fiber solutions can be fairly cost-effective in mass production, although the effort required for development of a product with high performance and reliable operation can be substantial due to various technical challenges – in particular, the handling of the strong optical nonlinearities.

Semiconductor Lasers

Some mode-locked diode lasers can generate pulses with femtosecond durations. Directly at the laser output, the pulses durations are usually at least several hundred femtoseconds, but with external pulse compression, much shorter pulse durations can be achieved. Mode-locked semiconductor lasers are also suitable for very high pulse repetition rates, e.g., tens or even hundreds of gigahertz. In most cases, however, the pulse energy is several limited to the picojoule region.

It is also possible to passively mode-lock vertical external-cavity surface-emitting lasers (VECSELs); these are interesting particularly because they can deliver a combination of short pulse durations, high pulse repetition rates, and sometimes high average output power. Their pulse energies can be much higher than for edge-emitting diode lasers, but still much lower than for solid-state bulk lasers in particular.

Frequency-converted Sources

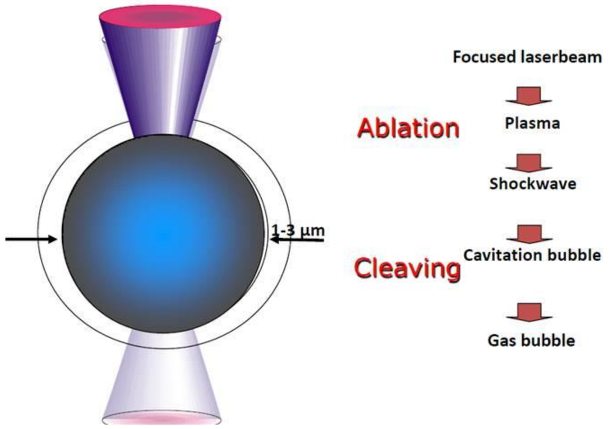
Some femtosecond laser devices strictly speaking not just a femtosecond laser, because they contain essential additional components such as an optical amplifier or means for nonlinear frequency conversion in order to get into other wavelength regions. For example, some devices contain asynchronously pumped optical parametric oscillator, which allows for the generation of widely wavelength-tunable radiation.

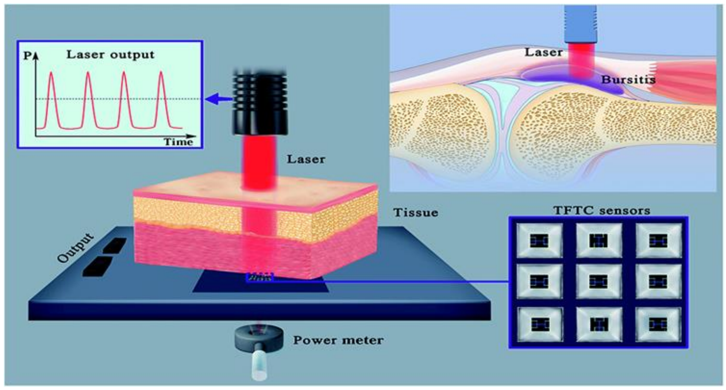
Other Types

More exotic types of femtosecond lasers are color center lasers and free electron lasers. The latter can be made to emit femtosecond pulses even in the form of X-rays.

Principles of Femtosecond Laser:

Femtosecond (FS) laser is an infrared laser with a wavelength of 1053nm. FS laser like Nd: YAG laser works by producing photo disruption or photoionization of the optically transparent tissue such as the cornea. Application of either FS laser or Nd: YAG laser results in the generation of a rapidly expanding cloud of free electrons and ionized molecules. The acoustic shock wave so generated results in disruption of the treated tissue. However, the two lasers differ significantly in the amount of collateral damage they cause. Nd: YAG laser has a pulse duration in the nanosecond range (10^{-9} second) whereas FS laser has pulse duration in the femtosecond range (10^{-15} second). Reducing the pulse duration reduces the amount of collateral tissue damage. In fact, collateral damage with FS laser is 106 times less than with the Nd:YAG laser. This makes FS laser safe for use in corneal surgeries which require exquisite precision.





Applications of Femtosecond Lasers:

Is a very wide range of applications of femtosecond lasers, exploiting quite different properties of the pulses. In the following, we give some typical examples.

1.Laser Material Processing

In laser material processing, femtosecond pulses have substantially higher peak powers than picosecond pulses of the same pulse energy. Therefore, the material can be evaporated even more quickly, which gives a potential for further improved processing quality in various situations – although that quality also depends on other factors (e.g. detailed choice of processing strategy and parameters) and is not always better than with picosecond pulses. A definite advantage, however, is seen in processing extremely fine structures with tightly focused femtosecond pulses: one can rapidly remove some material while other materials only a few microns away remains unaffected.

2. Medical Applications

Femtosecond lasers are also used in medical application areas, mainly for laser surgery. For example, it is now common to use femtosecond pulses for eye surgery (vision correction), e.g., in the form of femto-LASIK or cataract surgery. It is another area where the extremely short pulse durations are advantageous.

3.Laser Microscopy

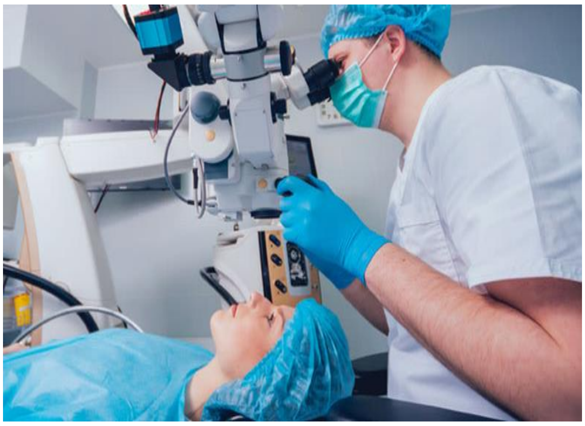
Femtosecond lasers have also become quite important for laser microscopy, e.g. in the form of fluorescence microscopy. Here, one frequently utilizes multiphoton excitation (based on multiphoton absorption), where very short pulse durations are quite advantageous. It is also possible to use stimulated Raman scattering (SRS spectroscopy).

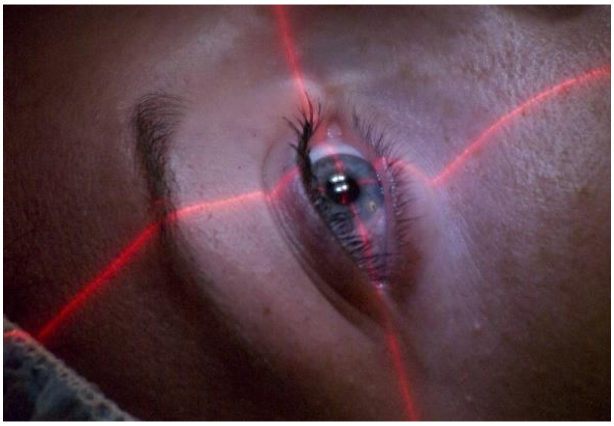
4.Telecommunications

In the area of optical fiber communications , femtosecond lasers can be used in different ways. For example, it is possible to realize dense wavelength division multiplexing (DWDM) with a very large channel count (sometimes >1000) by spectral slicing of broadband femtosecond pulses. By applying time division multiplexing in addition, one can achieve extremely high bit rates of >1 Tbit/s.

Clinical Application

FS laser has a wide range of applications in corneal refractive surgery. This includes LASIK flap creation, astigmatic keratotomy (AK), channel creation for implantation of intrastromal corneal ring segments (ICRS), presbyopia correction, femtosecond lenticule extraction (FLEx), small-incision lenticule extraction (SMILE), and intrastromal presbyopia correction (INTRACOR). Besides FS lasers are also being used in laser-assisted anterior and posterior lamellar keratoplasty, cutting of donor buttons in endothelial keratoplasty, customized trephination in penetrating keratoplasty, wound construction, capsulorrhexis in cataract surgery, and nuclear fragmentation in cataract surgery. In this article, we will discuss the application of FS laser in LASIK surgery.

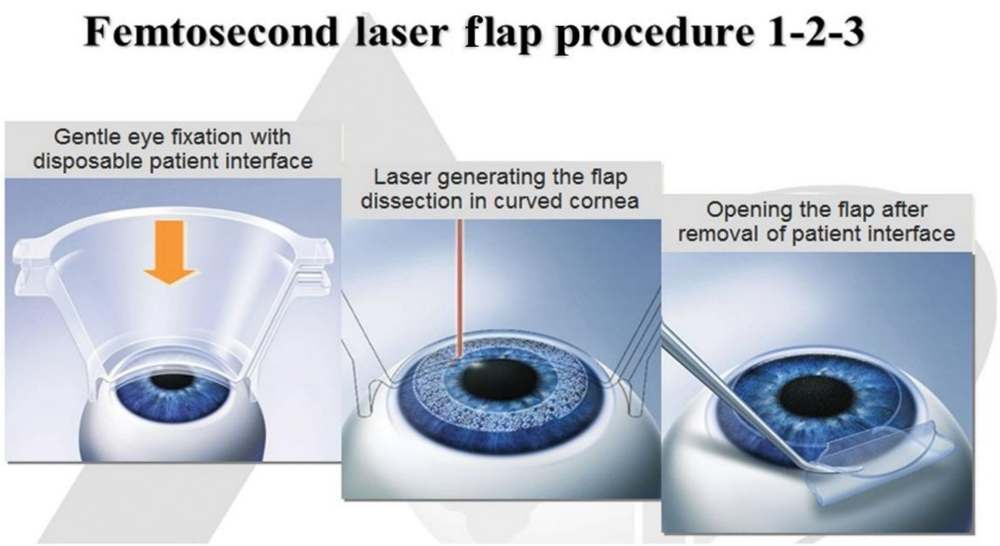




LASIK flap creation

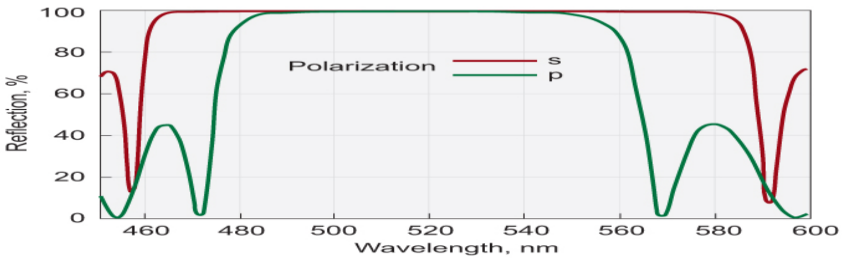
LASIK, which stands for laser in-situ keratomileusis, is a popular surgery that can correct vision in people who are nearsighted or farsighted, or who have astigmatism. It's one of many vision correction surgeries that work by reshaping your cornea, the clear front part of your eye, so that light focuses on the retina in the back of your eye.

The suction ring is centered over the pupil and suction is applied once proper centration of the ring has been ensured and verified. The docking procedure is then initiated while keeping the suction ring parallel to the eye. An applanating glass contact lens is used to stabilize the globe and to flatten the cornea. It is important to achieve complete applanation of the cornea to avoid an incomplete flap or other flap related complications. Once the laser's computer has confirmed centration, the surgeon administers the FS laser treatment. Each pulse of the laser generates free electrons and ionized molecules leading to formation of microscopic gas bubbles dissipating into surrounding tissue. Multiple pulses are applied next to each other to create a cleavage plane and ultimately the LASIK flap. Suction is then released. A spatula is carefully passed across the flap starting at the hinge and sweeping inferiorly to lift the flap for excimer laser ablation.



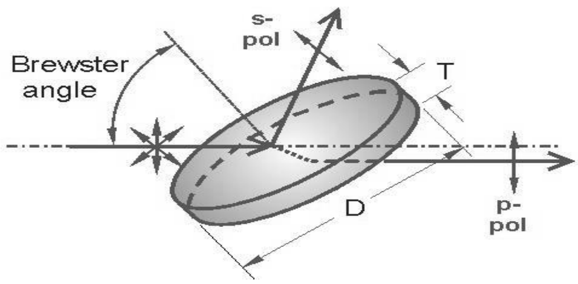
Femtosecond Laser Components:

- **Femtoline Mirrors:** Femtoline laser mirrors are designed to be used in femtosecond laser applications. You will find a wide selection of low GDD ultrafast mirrors and broadband low GDD ultrafast mirrors, dual band mirrors, harmonic separators, output couplers, rear mirrors, beam splitters for fundamental wavelengths of Ti:Sapphire and Yb:KGW/KYW lasers and their doubled, tripled or quadrupled frequencies. Femtoline laser mirrors are coated using electron beam multilayer dielectric or ion beam sputtering technologies.

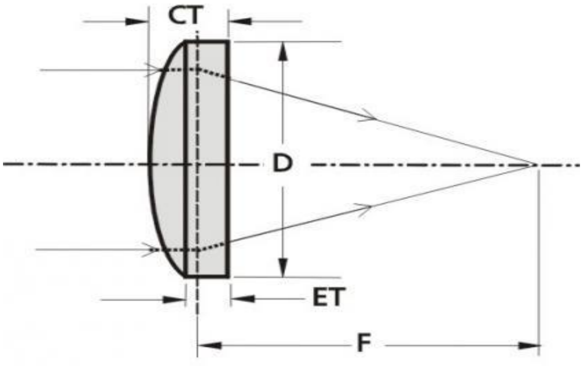


- **Femtoline Lens Kit:** Femto Line lens kits include 15 or 40 pieces of the most popular of 1 inch diameter spherical lenses made of UVFS optical material. Each FemtoLine lens kit consists of four basic types of lenses: plano-convex, biconvex, Plano-concave and biconcave.

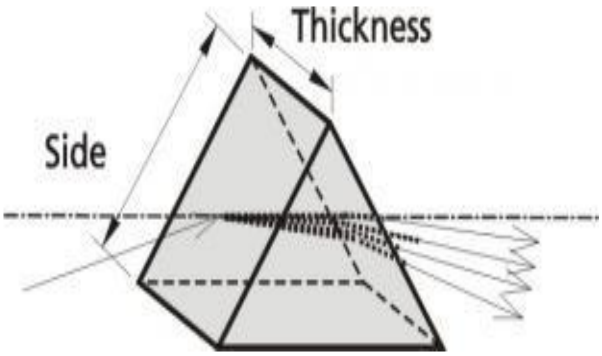
- **Femtoline Polarizing Optics:** Thin film laser polarizers (TFP) coated for 343 nm, 515 nm, 800 nm, 780-820 nm, 1030 nm, 1010-1050 nm wavelengths. We also offer a wide choice of zero order optically contacted or air-spaced, dual wavelength, multiple order and low order waveplates made from high quality crystalline quartz.



- **Femtoline Thin Lenses:** FemtoLine series thin plano-convex or Plano-concave lenses are made of UVFS. Thin lenses are designed for applications with ultrashort femtosecond pulses and feature low group delay dispersion (GDD). Thin lenses are available uncoated, coated with anti-reflective or broad band antireflective coatings.



- **Femtoline Prism:** FemtoLine series laser dispersing prisms can be used inside the laser cavity operating on very low gain laser transitions, where even slight reflection losses may be intolerable.



- **Femtoline Non linear and laser crystals:** FemtoLine product group includes a selection of nonlinear and laser crystals for femtosecond applications.

Unique Features

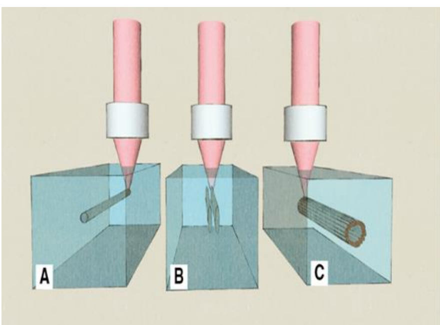
Imaging: Ophthalmic femtosecond lasers use a 3-D scanning procedure for tissue cutting. The same 3-D beam delivery used to disrupt tissue can also be used to image the cutting process before, during, and after surgery. The target tissue can be scanned for imaging without the addition of scanning mirrors or lenses. The first-generation of femtosecond laser cataract surgery already makes use of this unique feature by passing an optical coherence tomography (OCT) beam along the path of the laser beam to image the target tissue. This can be done before surgery to navigate the laser pulses.

This same feature is not yet in use in corneal refractive surgery femtosecond lasers, but it will no doubt be introduced as OCT technology becomes more affordable. Currently, only one femtosecond laser corneal surgical platform includes an imaging function, the Cornea Surgeon (Rowiak GmbH), which prepares corneal donor tissue for keratoplasty.

Femtosecond lasers can also be used to perform second harmonic imaging and multiphoton fluorescence imaging to supply high-resolution images, with the capability to deliver information about the anatomy as well as the metabolic conditions of the tissue.

Turbid tissue: Turbid corneal tissue induces very strong scattering. Fortunately, with long infrared wavelengths, scattering is very low, allowing turbid tissue to be processed at its surface, in deeper layers, and even in sclerotic crystalline lenses and scleral tissue.[9-11] In the future, ophthalmologists may be able to use this function of the femtosecond laser to treat glaucoma with novel surgical procedures.

Processing speeds: Today, ophthalmic femtosecond lasers can deliver repetition rates in the kilohertz range with sufficiently high pulse energies. In the future, it may be possible to use laser delivery repetition rates in the megahertz range, further reducing treatment times.



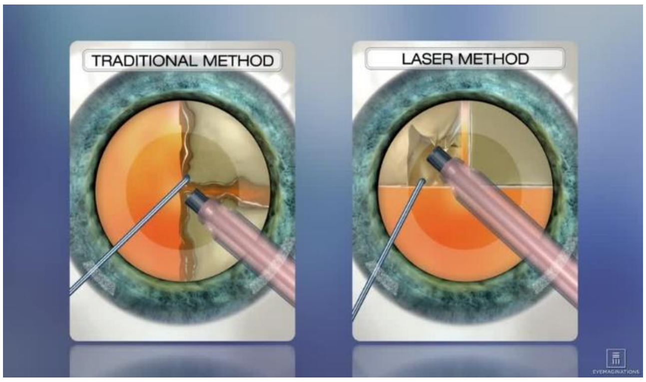
Advantages

More than 55% of all LASIK procedures in 2009 were performed with FS laser. The number was 30% in 2006. FS laser offers several advantages over the conventional microkeratomes and is gaining popularity across the globe.

Major advantages of FS laser

1. Reduced incidence of flap complications like buttonholes, free caps, irregular cuts etc.
2. Greater surgeon choice and control over flap diameter and thickness, side cut angle, hinge position and length
3. Increased precision with improved flap safety and better thickness predictability
4. Capability of cutting thinner flaps to accommodate thin corneas and high refractive errors
5. Absence of moving parts

Other advantages include stronger flap adherence, better contrast sensitivity, decreased incidence of epithelial ingrowth, less increase in IOP required, lesser incidence of dry eyes, lesser haemorrhage from limbal vessels less likely, and the ability to retreat immediately if there is incomplete FS laser ablation. Loss of suction during FS laser LASIK flap creation is easier to handle and the suction ring may be reapplied and treatment resumed immediately in many cases. Studies have shown FS laser to be safe and the visual and refractive outcomes of FS laser LASIK are equivalent to microkeratome LASIK. Use of the laser minimizes the risk of damage to adjacent tissues when compared to traditional surgical methods. Therefore, healing time is quicker and there is less post op discomfort than with traditional methods which require a scalpel and/or cauterizing procedure. The femto laser precision is due to the new real time optical coherence tomography software program, which covers the whole anterior segment, up to the posterior capsule of the crystalline lens.



Disadvantages and Unique Complications

As described above, FS laser has a lot of advantages over microkeratome LASIK and is gaining more and more acceptance worldwide. However, the technique presents with its unique set of disadvantages and related complications. Flap creation with FS laser usually takes longer than microkeratome LASIK, however newer high frequency FS lasers have overcome this disadvantage. Some of the more significant complications unique to FS laser are

1. **Opaque bubble layer (OBL**): Gas bubbles routinely accumulate in the flap interface during FS laser treatment, but occasionally they may dissect into the deep stromal bed. This may interfere with the ability of the excimer laser eye tracker device for tracking and registration. Conversely the bubbles may seep into the anterior chamber by dissecting through the trabecular meshwork. The incidence of OBL can be reduced by use of the raster or centripetal spiral patterns and peripheral gutters programmed into the cut.

2. **Transient light sensitivity syndrome (TLSS):** Also called as good acuity plus photosensitivity (GAPP). TLSS usually occurs days to weeks after FS laser LASIK. Patients present with extreme photophobia and good visual acuity with paucity of clinical findings on exam. It resolves without sequel but requires aggressive topical steroids for weeks. Proposed mechanism is either an inflammatory response of the surrounding tissue to the gas bubbles or biochemical response of the keratocytes to the near-infrared laser energy.

3. **Micro-irregularities** on the back surface of the FS laser LASIK flap can cause “rainbow glare”. Patients complain of coloured bands of light radiating from a white light source. These glares are usually inconsequential in terms of their visual impact

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4. **Photo disruption-induced microscopic tissue injury** and ocular surface inflammatory mediators may cause lamellar keratitis in the flap interface. Lamellar keratitis tends to have little effect on visual acuity but flap necrosis following this complication has been reported in literature. The mild effect on visual acuity usually persists for less than one week after the surgery. Other disadvantages include increased cost, need to acquire a new skill on the part of the surgeon, increased difficulty in lifting the flap if retreatment is required, and a low risk of interface haze and interface stromal irregularities.

Future Scope and Conclusion:

Femtosecond lasers (fs-lasers) have developed rapidly, and several approved laser systems are on the market. The spectrum of applications has also expanded considerably. In corneal surgery, the precise intrastromal use of the fs-laser has opened numerous new applications and led to totally new surgical standards. The fs-laser is an infrared laser that functions with much less heat stress than other laser systems. Its use enables surgeons to separate corneal tissue precisely without a scalpel. The tissue should be largely transparent so that the laser can make precise incisions at any site on the cornea. At the clinic for refractive and ophthalmic surgery in Duisburg, Germany, we use a modern 40khz version of the Femtec fs-Laser (20/10 Perfect Vision, Heidelberg, Germany). When using the fs-lasers now available on the market, the cornea is subjected to applanation, leading to vision blackouts during treatment. The Femtec fs-laser has a patented, curved patient interface. Thanks to the curvature, only moderate suction is needed to couple the eye to the laser. The treatment itself is performed with minimal applanation and therefore without vision blackouts during the surgeries. The procedures performed are endothelium-sparing. In our opinion, there are two approaches to future applications of fs-lasers. One is to survey the present practical applications closely and further improve and develop existing surgical techniques. We will start with this approach and illustrate it with case studies. The second approach entails examining current research for which concrete scientific publications are available. However, it must be questioned to what extent the, admittedly very attractive, approaches can be applied in practice and when – if ever – this will be the case. This preview will conclude our overview.

FS laser is being widely used in various ophthalmic surgical procedures. Advances in technology like lower energy systems with faster firing rates will increase the versatility and precision of the laser systems. This will further reduce ancillary tissue damage and make the surgery safer. As with any other technology, competition will likely bring down the cost of the equipment making the price per case less expensive. FS lasers hold great promise and its applications are continuing to evolve and expand in ophthalmology.

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