LASER

1. BASIC PRINCIPLES

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HISTORICAL BACKGROUND

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The underlying process for Stimulated Emission, was first proposed by Albert Einstein in 1917. The working principles of lasers were outlined by the American physicist Arthur Schawlow and Charles Hard Townes in their 1958 patent application. The patent was granted but was later challenged by the American physicist and engineer Gordon Gould. In 1960 the American physicist Theodore Maiman[1] observed the first laser action in solid ruby. A year later a helium-neon gas laser was built by the Iranian-born American physicist Ali Javan. Then in 1966 a liquid laser was constructed by the American physicist Peter Sorokin. The U.S patent office court in 1977 confirmed one of Gould's claim over the working principles of the laser. In mid 1960s Francis L'Esperance[2] of New York and Little and Zweng[3] at Palo Alto developed argon laser. It was commercially introduced for use in 1971. During the next two decades several other thermal lasers were developed namely argon green, krypton red and tunable dye lasers. In early 1970s saw the introduction of the so called cold-lasers for the use of photodisruption or optical breakdown. Frankhausers[4] in Switzerland and Aron Rosa[5] in France developed the high powered neodymium YAG laser. In 1983 Trokel[6] in United States developed the Excimer laser.

LASER APPLICATIONS

The use of lasers is restricted only by imagination. Lasers have become valuable tools in industry, scientific research, communication, medicine, the military, and the arts.

1. Industry

Powerful laser beams can be focused on a small spot with enormous power density. Consequently, the focused beams can readily heat, melt, or vaporize material in a precise manner. Lasers have been used, for example, to drill holes in diamonds, to shape machine tools, to trim microelectronics, to heat-treat semiconductor chips, to cut fashion patterns, to synthesize new material, and to attempt to induce controlled nuclear fusion

Lasers are used for monitoring crystal movements and for geodetic surveys. They are also the most effective detectors of certain types of air pollutants. In addition, lasers have been used for precise determination of the earth-moon distance and in tests of relativity.

2. Scientific Research

Because laser light is highly directional and monochromatic, extremely small amounts

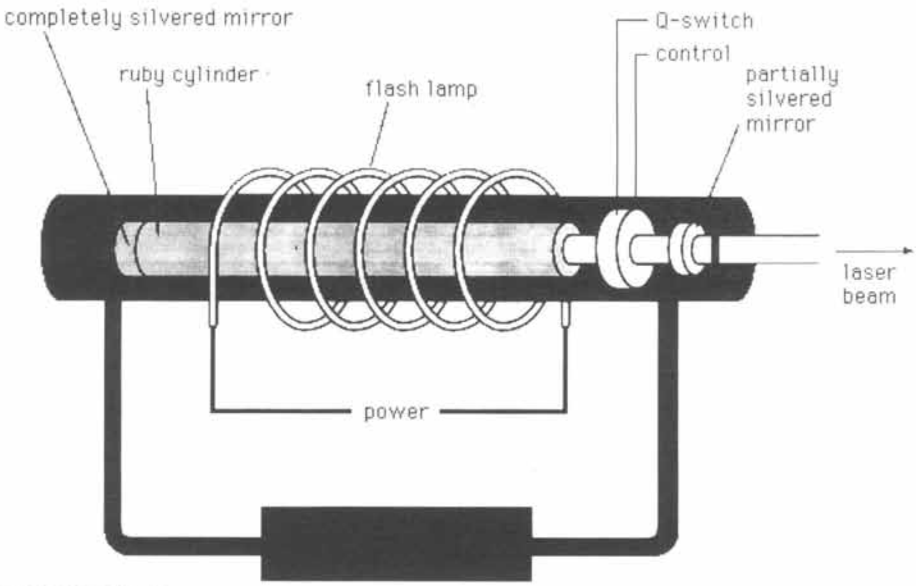

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Fig. 1. Components of a typical solid ruby laser

of light scattering or small frequency shifts caused by matter can easily be detected. By measuring such changes, scientists have successfully studied molecular structures of matter. With lasers, the speed of light has been determined to an unprecedented accuracy

3. Communication

Laser light can travel a large distance in outer space with little reduction in signal strength. Because of its high frequency, laser light can carry, for example, 1000 times the television channels today carried by microwaves. Lasers are therefore ideal for space communications. Low-loss optical fibers have been developed to transmit laser light for earthbound communication in telephone and computer. Laser techniques have also been used for high density information recording. For instance, laser light simplifies the recording of a hologram, from which a three-dimensional image can be reconstructed with a laser beam. Lasers are also used to play audio compact disks and videodiscs.

TABLE – I

RADIOMETRIC TERMINOLOGY OF LASERS

Term	Unit
Radiant energy	Joule
Radiant power	Watt
Radiant energy density	Joules/cm^2
Irradiance	Watts/cm^2

Watt = joule/sec

Joule = watt x sec

4. Medicine

Intense, narrow beams of laser light can cut and cauterize certain tissues in a small fraction of a second without damaging the surrounding healthy tissues. They have been used to "weld" the retina, bore holes in the skull, vaporize lesions, and cauterize blood vessels. Laser techniques have also been developed for lab tests of small biological samples.

TABLE – II

PHOTOCOAGULATING LASERS

Laser	Wavelength (nm)
Argon blue	488.0
Argon green	514.5
Double YAG	532.0
Krypton yellow	568.0
Krypton red	647
Diode	780–850
Tunable	570–630

5. Military

Laser guidance systems for bombs, missiles, aircraft, and satellites are being studied and constructed. The use of laser beams has been proposed against hostile ballistic missiles.

The basic Principles of Lasers

There are three basic components of laser (Fig. 1).

1. Laser medium
2. A method of exciting the atoms or molecules in the medium
3. An optical cavity around the medium which acts as resonator.

The laser medium may be solid, liquid or gas. Solid lasers are crystal such as ruby or neodymium YAG. Liquid lasers are organic dyes such as Rhodamine B. Gas lasers are argon, krypton, He-Ne, carbon dioxide and argon fluoride.

The exciting methods consist of light in case of solid lasers and electricity in case of gas lasers.

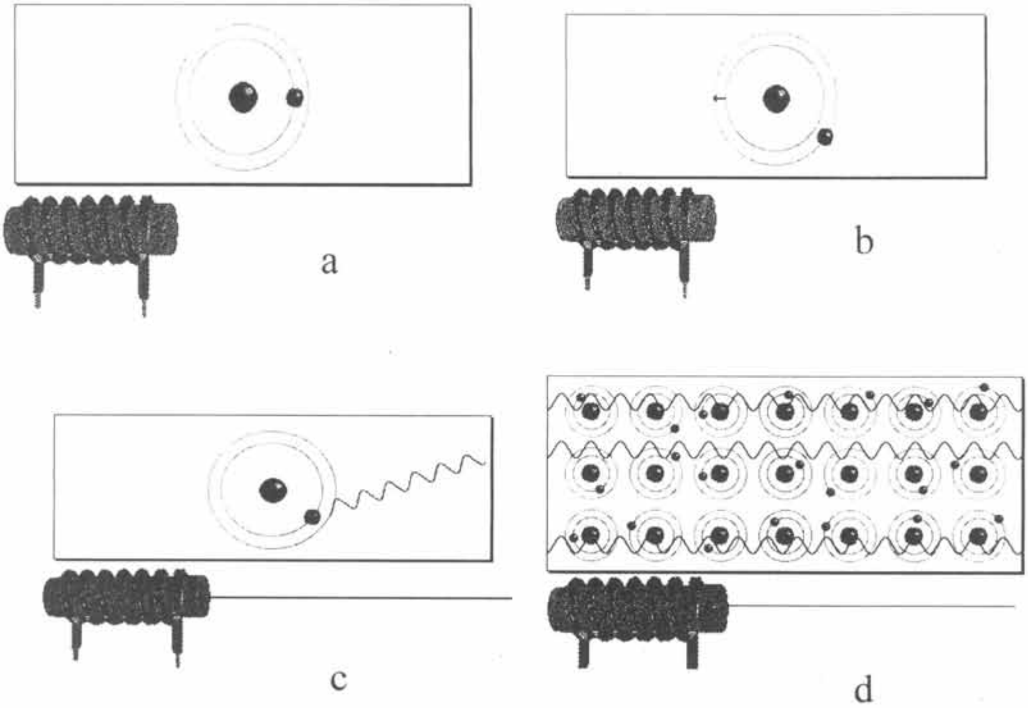

Fig. 2. The formation of laser light. a) Atom in ground state with electron in inner orbit. b) Electron pushed into outer orbit by excitation with xenon flash. c) Electron falls back into inner orbit releasing photon. d) Multiple photons released.

TABLE – III

EXCIMER LASERS

Laser	Wavelength (nm)
Argon fluoride	193
Krypton fluoride	248
Krypton chloride	222

The optical cavity consists of mirrors on each side which are precisely aligned. One mirror is completely reflective and the other is only partially reflective. The atoms in the laser medium are normally in an inactive or ground state. When these atoms or molecules are excited, the electrons from inner orbit are pushed into the outer orbit and the atom is now in the excited state. This excited state remains only for a brief period of time and the electrons fall back into the inner orbit. In their return to ground state they release energy in form of monochromatic rays or photons. These photons strike other atoms causing them to release more photons. These photons move back and forth between the mirrors thus producing additional photons. When similar photons in the optical cavity reach a certain energy level, operation of the laser is possible. The shutter in the partially reflective mirror then allows the laser beam to be released into the delivery system (Fig. 2).

Properties of the Laser light

Lasers are the one of the many sources of light energy. Its unique properties make it very useful for medical applications. These properties are monochromaticity, directionality, coherence, polarization, and intensity.

1. Monocromaticity

Laser emits light of only one wavelength or some times a combination of several wavelengths. Thus a monochromatic beam is obtained. Although the

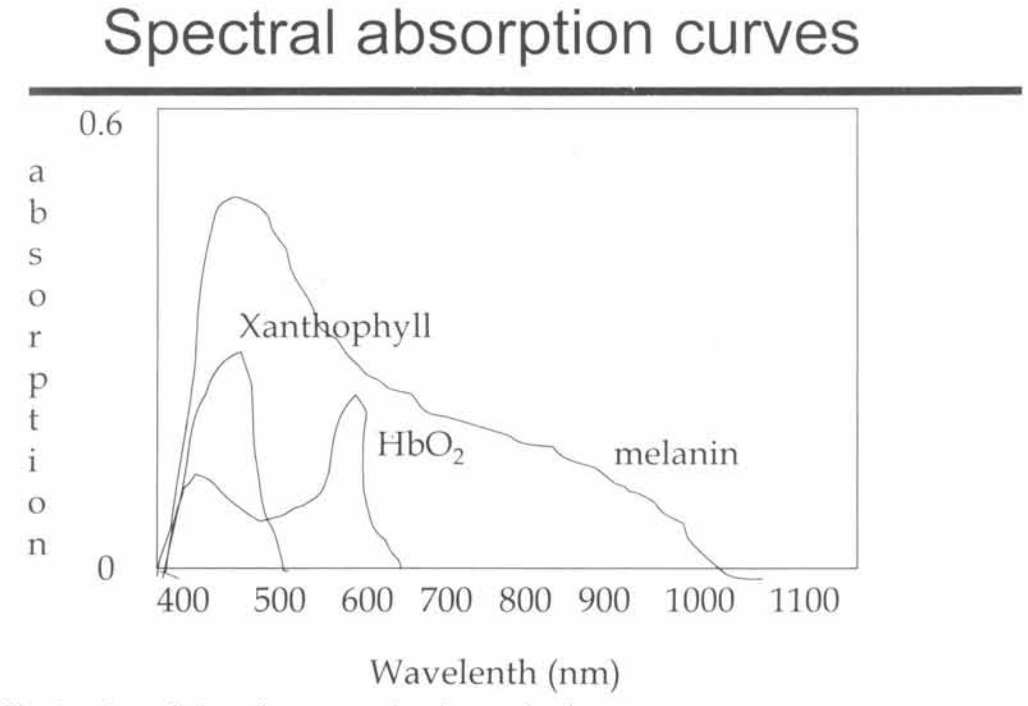

Fig. 3. Spectral absorption curves of various ocular tissues.

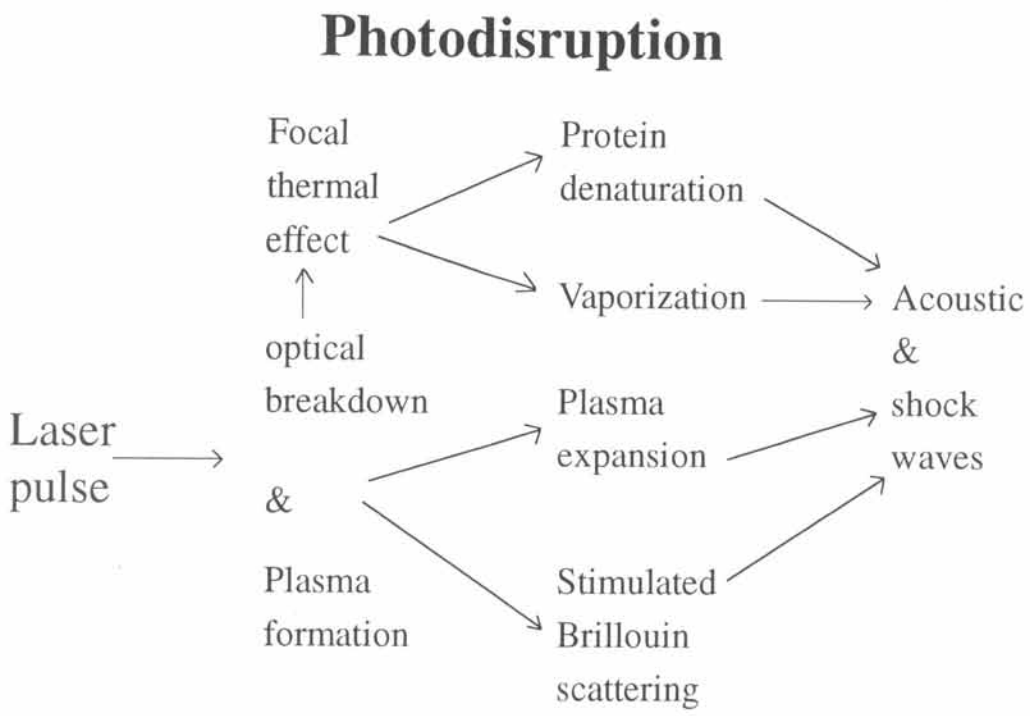

Fig. 4. Various mechanisms of damage in ophthalmic short-pulsed Nd: YAG laser.

wavelength spread is not infinitely small, a gas laser emission line can be as narrow as 0.01 nano-meters, as compared to the wavelengths over a 300 nano-metres span that of a white light. This monochromaticity avoids chromatic aberration in the lens system. This monochromatic light can be focused to a very small spot as compared to that of white light.

2. Directionality

Laser emits a narrow beam of light that spreads very slowly. This process serves a very efficient mechanism for collimating the light. A typical laser has a beam divergence of 1 milli-rad, which indicates that the beam increases in width by 1 mm in diameter for every meter it traveled. Directionality makes it easy to collect all the light energy in single lens system and to focus this light into a small spot.

3. Coherence

This is that the waves making up the beam have the same wavelength and are in phase with each other. The degree of coherence is the extent to which the electromagnetic field of the light wave varies regularly and predictably in time and space. Coherence of laser light is utilized to create the interference fringes of the ophthalmic diagnostic laser interferometer. The therapeutic ophthalmic laser's coherency, like directionality, is important because of the improved focusing characteristics.

4. Polarization

Many lasers emit linearly polarized light. Polarization is incorporated in the laser system to allow maximum transmission through the laser medium without loss caused by reflection. The specific polarization of light beam is not currently utilized in medical applications. However, the most commonly employed electro-optical Q-switches work by manipulations of polarized windows in the beam path.

5. Intensity

The most important property of laser is brightness or intensity. Radian energy is measured in joule and radian power is measured in watts. One joule = 1 watt x 1 second or one watt = 1 J/second. The radiometric terminology of medical laser is given in table 1. The radiance takes into account not only the intensity of the source, but also the ability of the source to deliver the power into a small angular beam.

Modes of Laser operation

The rate of energy delivery in lasers is important in determining the interaction of laser radiation with the biological tissue. There are two modes:

1. Continuous wave lasers

These lasers deliver their energy in a continuous stream of photons when the shutter is opened, resulting in thermal reactions in the tissue. Ophthalmic lasers operating in this mode are termed thermal or photocoagulating, and include argon, krypton, carbon dioxide, infrared diode and Nd: YAG in free running mode.

2. Pulsed lasers

These lasers produce energy in pulses of a few tens of microsecond to a few milliseconds duration. The power of a laser can be increased either by increasing its energy or more practically by reducing the time over which the energy is delivered. The two principle means of compressing laser output in time to achieve high peak power are known as Q-switching and mode-locking.

a. Q-switched pulses of several nanoseconds duration cause ionization, mainly by focal heating of the target. At the focal point temperatures in excess of several thousands degree centigrade are achieved. Impurities in the target tissue enhance this process. There are a number of methods of Q-switching, including the use of rotating mirrors, saturable dyes, and acousto-optic modulators. The most common Q-switch is an electro-optic modulator known as Pockel's cells which applies voltage across a crystal to vary polarization. Polarity can be changed rapidly by 90 degrees, which makes the cell either transparent or opaque to the polarized laser beam.

The mode-locked pulses typically lasting 20 to 30 pico seconds have a different dominant mechanism to initiate ionization. The energy of each pulse is below optical breakdown threshold, but the accumulating effect of the pulse train is powerful enough to cause tissue disruption[8]. In ophthalmic applications the most common shutter is a saturable dye, used in a process called passive mode-locking. The dye has the property of absorbing low power light pulses but the dye bleaches and becomes transparent on exposure to high power light pulses.

Types of tissue reaction to laser light

There are three types of tissue reaction to laser light

Photocoagulation
Photodisruption
Photoablation

1. Photocoagulation

Recognition of the therapeutic powers of light followed initial appreciation of its toxicity. Solar retinitis was recognized and documented by the ancient Greeks. Plato quotes Socrates. "I thought that I must take care that I did not suffer as people who look at the sun during eclipse. For they are apt to lose their eyesight unless they look at the sun reflection in water or some such medium. That danger occurred to me. I was afraid that my soul might be completely blinded if I looked at things with my eyes and try to grasp them with my senses."[9]

Medical documentation of scotoma from sun's gazing came first from the ophthalmologist Bonetus who practiced in Geneva in 17th century[9]. Experimentation into solar retinitis began with Czerny[10] in 1867 and Deutschmann[11] 1882, who employed concave mirrors and convex lenses to focus sunlight in the retinas of rabbits.

Clinical therapeutic use of photocoagulation began with the pioneering work of Gerd Meyer-Schwickerath at the university of Hamburg. After observing macular damage in several patients after the solar eclipse on July 10, 1945, he recognized that the pigmented scar resembling the scar produced by diathermy and surmised that focused radiant energy could be used to create chorio-retinal lesions of clinical value. At that time he failed to find a suitable light source of high intensity enough to be focused to produce chorioretinal scars in the retina, so he turned to sunlight. His original sunlight photocagulator consisted of a Gallilean telescope with a mirror having a central aperture suspended on a universal joint in front of the ocular. Although this instrument produced the first successful clinical treatment, the frequency of cloudy days in Northern Europe made it impractical and his attention turned back to an improved carbon arc, and finally Xenon lamp. Although Xenon arc photoagulator introduced the concept of non-invasive surgery in ophthalmology, it had its limitation. Xenon arc produces white mixed light with an incoherent divergent beam. It generates a great amount of heat and thermal damage in the tissue, causing corneal and lens damage in the anterior segment and deep burns complicated by field defect in the retina. Its use was therefore limited to pan-retinal photocoagulation as the burns obtained were two gross to allow treatment in the macula or closed to the fovea. In addition treatment with Xenon arc photocoagulator is painful and an anaesthetic is invariably required. The development of lasers in the 1960s in the U.S.A provided a source of radiant energy highly suitable for use in ophthalmic microsurgery.

The effect of laser radiation on a particular target depends on the properties of both the laser and the target. The most important laser output parameters are wavelength duration and power. The wavelengths of some of the commonly used lasers for photocoagulation are given in table 2.

Most photocoagulating lasers run in continuous mode, that is their exposure time varies from 100-200 msec. Their power is measured in watts. For a given amount of power the shorter the time over which it is delivered, the greater is the tissue damage. The spot size may very·from 50 mm to 1 mm. The temperature rise produced by laser irradiation is a function of time, laser energy, and wavelength, and the optical and thermal properties of the absorbing tissue. Modest increases of 10°C to 20°C induce alteration of the genetic apparatus of cells, inactivation of enzymes, and denaturation of proteins and nucleic acids which lead to necrosis, haemostasis and coagulation[12]. Immediate effects are visible ophthalmoscopically because of focal increases in necrotic cells and mechanical disruption of the adjacent neurosensory retina, that interferes with normal transparency.[13]

Delayed effect results from inflammation, oedema, and repairing process. Repair of laser thermal injury to the retina begins within a few hours with the appearance of sub-retinal macrophages in the inter-receptor matrix.[14] Retinal pigment epithelial cells (RPE) increase in size and possibly undergo mitosis to cover the area of damaged cells. Cell division also occurs in the endothelial cells of the chorio-capillaris, choroidal fibroblasts and melanocytes and the supportive glial cells as a secondary response to neuronal cell loss. While photocoagulation may destroy the blood retinal barrier at the level of RPE, if the burns are not too sever, reformation of zonula occludens, junctions between adjacent proliferated RPE cells, will restore the barrier.[15]

Spectral absorption curves of various ocular tissues is given in figure 3. Anderson and Parrish[16] proposed one method of enhanced absorption, called selective phototheromolysis in which selective tissue damage is determined not by the precise aiming by the laser beam but by the unique absorption properties of the intended target tissue. If the target has an absorption coefficient at least twice that of the surrounding tissue at a given wavelength, preferential absorption will result in thermal damage localized to the target if the radiation is delivered for the duration similar to or less than thermal diffusion constant.

Another method of increased absorption of the laser light by target tissue is by dye enhancement. Intravenous injection of certain exogenous dyes can substantially increase the specificity and effectiveness of certain laser procedures. Inodocyanine green has an absorption peak at 805nm. The dye's predilection for neovascular nets and their environ makes it a useful exogenous chromophore for diode laser selective photocoagulation and thermal enhancement of membrane closure.[17] In patients receiving indocyanine green enhanced diode laser photocoagulation of SRVN, minimal deep retinal whitening is noted acutely, followed by a chorioretinal scar formation.[18] Closure of the neovascualr membrane is accomplished using an ophthalmoscopic end point treatment of a mild gray white colour change in the lesion, rather than the intense retinal whitening commonly used.

2. Photodisruption

If light exposure times are very short that is in nano-seconds or pico-seconds and the energy is enough, damage produced due to ionization is usually called photodisruption. While linear absorption of light can produce thermal denaturation, vaporization, shock waves, and acoustic waves which cause damage to tissue, the achievement of a threshold optical power density which causes electrostriction and dielectrict breakdown, in normally transparent tissue, can produce even more intense effects. With a Nd: YAG laser it is easy to show optical breakdown in gases and liquids by focusing the beam to a small enough spot. Breakdown is the ionization of medium through intense electric fields caused by the optical beam. This ionized medium is commonly called plasma which further absorbs the beam and thus most of the energy in the beam is deposited in the region of the break-down.

Krasnov was the first to demonstrate that a high peak power pulses could be used to produce clinically desirable disruption of ocular structures. In 1972 he reported the use of a Q-switched ruby laser to treat the trabecular meshwork of eye with open angle glaucoma.[19] Krasnov coined the term of cold laser which is a misnomer, since plasma results in a very localized temperature increases in excess of 10,000°C. Subsequent development has shown that for a variety of technical reasons, the Q-switched ruby laser is not the optimal source for building a clinically practical ophthalmic photodisruptor. Krasnov was successful in rupturing the anterior lens capsule in the rabbit eyes but was unable to do so in human eyes involved by senile cataract. Gaasterland was able to build a custom Q-switched ruby laser system that was successfully used for photodisruption. However, because the laser output could be brought only to a focal spot of 175 mm, energies many times greater than necessary with current Nd: YAG photodisruptor were required for membranectomies. In addition it was necessary to wait three minutes between laser shots so that the ruby rod could cool to allow subsequent shots to be reproducible in energy level. It was Aron Rosa in France and Frankhausers in Switzerland who developed the practical and highly desirable Q-switched and mode-lock neodymium YAG laser for its use in ophthalmology especially for posterior capsulotomy after extra-capsular extraction.

Several mechanisms may combine to generate pressure waves radiating from the zone of optical breakdown. Foremost among these is the rapid plasma expansion that begins as hypersonic shock waves.[20-22] A second weaker source of hypersonic and sonic waves is stimulated Brillouin scattering in which the laser light generates the pressure waves that scatters it.[23, 24] The focal heating can lead to a phase change that is vapourization and melting and thermal expansion both of which generate acoustic waves.[25-27] The electric field of the laser light if sufficiently strong will deform a target through electro-striction and through radiation pressure caused by momentum transfer from protons to atoms[28] (Fig. 4)

3. Photoablation or Photodecomposition

The term ablation is often used indiscriminately to refer to many laser procedures including photocoagulation. However, it should be reserved when there is involvement of actual removal of tissue.

a. Carbon dioxide laser

Ophthalmic investigation of carbon dioxide laser followed soon after its development in 1964.[29] It's wavelength is 10,600 nm. It is strongly absorbed by water which makes it more useful in any water containing tissue and is currently employed in dermatology, gynaecology, neurosurgery, and otolaryngology. Heat diffusion away from the target area coagulates adjacent vessels and provide haemostasis which is particularly useful in patients with bleeding disorders. Carbon dioxide laser has been employed either experimentally or clinically to treat ophthalmic pathology ranging from the eyelids and adnexa to the retina.[33-33] The major disadvantage of carbon dioxide laser is that current fiber-optics are not capable of effectively transmitting at this wavelength, necessitating the use of less flexible articulated arms. Also smoke and steam often develop and must be vented.

b. Excimer Lasers

Excimer or excited dimmers are molecules with bound upper states and weakly bound ground states. The most common excited molecules exhibiting laser action are rare gas excimer, such as fluoride and xenon, which emit radiation at 157nm and 170nm, respectively. Such lasers, however, are impractical for ordinary laboratory use, not least because oxygen absorption below 190nm precludes working in room air. The best performance has been demonstrated by excimers formed by the reaction of an excited rare gas atom with the halogen molecules, in which the rare gas atom acts as the corresponding alkali metal and becomes very reactive in the presence of halogen containing molecules.[34] Various excimer lasers with their wavelengths is given in table 3. Since the early 1980s it has been demonstrated that excimer lasers are capable of precisely etching submicrometer patterns in a variety of polymer materials.[35-37]

Srinivasan[38] has termed this controlled removal of material, in which molecules on the irradiated surface are broken into small volatile fragments, "ablative decomposition". It is believed, is caused by a combination of high absorption for far-UV radiation possessed by organic polymers, which limit the depth of radiation's penetration, and the high quantum yield for bond breaking, which results in the formation of numerous fragments in a small volume near the surface.[39] Ablation is thought to result from the intense pressure build-up within this volume.[38,40,41]

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