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Review of lasers application in dentistry

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SUMMARY
In this paper the mechanism of stimulated emission is described as the fundamental of laser technology. The types of lasers from the aspect of their operation are also given. The particular attention is paid to dental lasers and their effect on healing processes in bone, dentin, enamel etc.

Keywords: lasers; dental lasers; bone regeneration; hard dental tissue; soft tissue

INTRODUCTION

Based on Albert Einstein's theory of spontaneous and stimulated emission of radiation, Maiman developed the first laser prototype in 1960 [1]. His device used a crystal medium of ruby that emitted a coherent light when it was stimulated by energy. A bit later, in 1961, Snitzer published his paper with the prototype of the Nd:YAG laser [2]. The first application of laser on dental tissue was reported by Goldman et al. and Stern and Sognnaes [3, 4]. In their papers, the effects of the ruby laser on enamel and dentin were described. Further application of lasers in dentistry was studied in the paper published in 1985 by Myers and Myers, where *in vivo* removal of dental caries using a modified ophthalmic Nd:YAG laser was presented [5]. Several years later, it was recommended that Nd:YAG laser could be used for oral soft tissue surgery, due to its effect on healing of various dental diseases [6].

The purpose of this review was to analyze wide area of laser applications and principle of its specific functions, as well as application of lasers in treating common oral soft and hard tissue problems.

Basic laser theory

Laser is the acronym of the words "Light Amplification by Stimulated Emission of Radiation". Lasers have come a long way since Albert Einstein described the theory of stimulated emission in 1917. Einstein in his theory of stimulated emission predicted that excited atoms could convert stored energy into light in the process by which an incoming photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level. The generated energy transfers to electromagnetic field, creating a new photon. This process has two important characteristics. First, it is multiplicative, because one photon induces two photons. If these two photons interact with two other excited atoms, this will yield a total of four photons, and so forth (Figure 1). Second and most importantly, these two photons have identical properties: wavelength, direction, phase, and polarization. This ability to "amplify" light in the presence of a sufficient number of excited atoms leads to "optical gain" that is the basis of the laser operation [7].

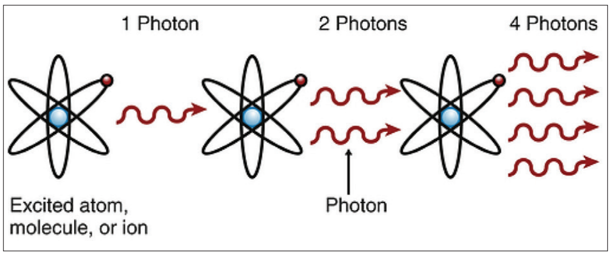

Figure 1. Light amplification by stimulated emission of radiation
Slika 1. Amplifikacija svetlosti stimulisanom emisijom zračenja

Figure 2 shows three and four level lasers. In three level lasers, a burst of energy excites electrons in more than half of atoms from their ground state to a higher state, creating a population inversion. The electrons then drop into a long-lived state with slightly less energy, where they can be stimulated to quickly shed excess energy as a laser burst, returning electrons to a stable ground state. In four level lasers a sustained laser beam can be achieved by using atoms that have two relatively stable levels between their ground state and a higher-energy excited state. As in a three-level laser, atoms first drop to a long-lived metastable state where they can be stimulated to emit excess energy. However, instead of dropping to the ground state, they stop at another state above the ground state from which they can easily be excited back up to the higher metastable state, thereby maintaining the population inversion needed for continuous laser operation.

A wide range of solid, liquid and gas-phase materials have been discovered that exhibit gain under appropriate pumping. A laser generally contains *laser* resonator (or *la-*

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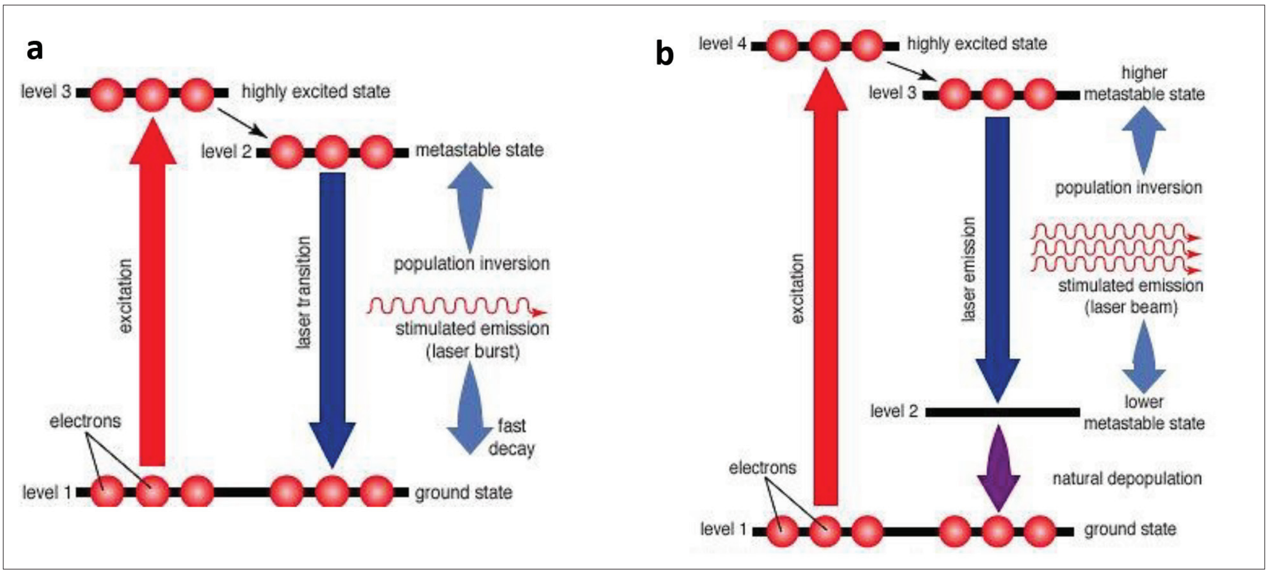

Figure 2. a) Three-level laser, b) Four-level laser
Slika 2. a) Laser sa tri nivoa energije, b) Laser sa četiri nivoa energije

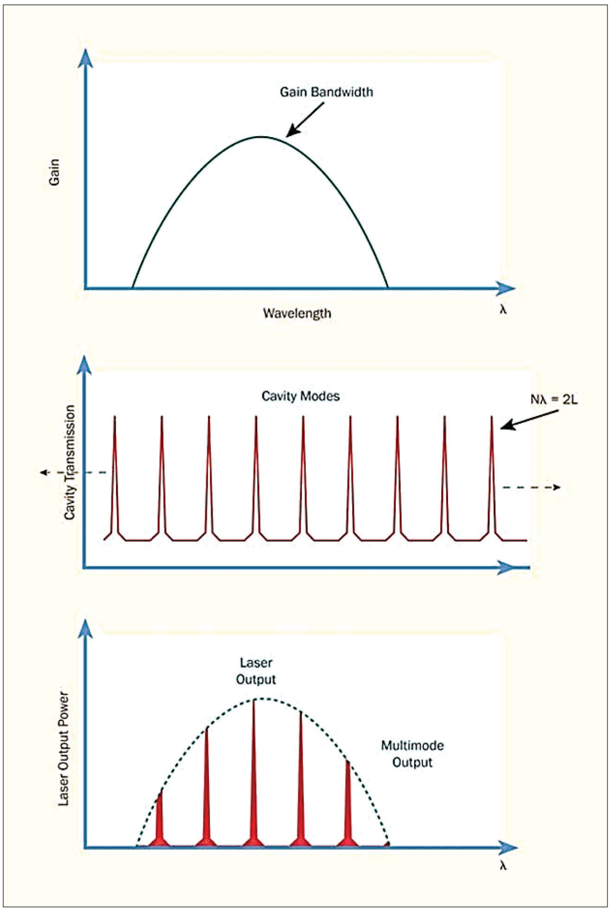

Figure 3. A resonant cavity supports only modes that meet the resonance condition, for cavity length. The output of a CW laser is defined by the overlap of the gain bandwidth and these resonant cavity modes.
Slika 3. Rezonantna kutija podržava samo modove koji postižu rezonantne uslove, za datu dužinu kutije. Izlazna snaga kontinualnog lasera definisana je preklapanjem opsega i modova rezonantne kutije.

ser cavity), in which laser radiation can circulate and pass a gain medium that compensates optical losses (Figure 3). Exceptions are a few cases where a medium with very high gain is used, so that amplified spontaneous emission extracts significant power in a single pass through the gain medium, such as excimer laser. Additionally, a laser resonator typically contains multiple laser mirrors, enabling multiple pass of generating photons, through its gain medium, and additional optical elements e.g. for wavelength tuning, Q switching mode, or locking. The laser mediums can be crystals, semiconductors, or gas enclosed in an appropriate confinement structure. It is placed along the optical axis of the resonator. This unique axis with very high optical gain becomes also the direction of propagation of the laser beam. A somewhat different example of a uniquely long (and flexible) gain axis is the fibre laser [8, 9].

Types of lasers

Lasers, from the aspect of its way of operation can be divided in three basic categories: continuous wave (CW), pulsed and ultrafast.

Continuous lasers

Continuous wave lasers produce a continuous, uninterrupted beam of light, with high stable output power. The exact wavelength of laser beam is determined by the characteristics of the laser medium. For example, CO_2 molecules readily excite at 10.6 μm, while neodymium-based crystals (like YAG or vanadate) produce wavelengths in the range between 1047 and 1064 nm. Additionally, each laser wavelength is followed by corresponding line-width, which depends mainly on the gain bandwidth of the lasing medium, filters and design of optical resonator. The specific wavelengths of the output beam within this gain bandwidth are determined by the longitudinal modes of the cavity. A laser that produces multiple longitudinal modes has a limited coherence, because different wavelengths cannot stay in phase over extended distances [10].

For some laser types with a narrow gain bandwidth, single-mode output is achieved with a very short resonant cavity. Generally, filtering elements are used to provide a preferential pass for only one mode generated into the cavity. The most common type of filter is called an etalon. Using various sophisticated design enhancements, it is possible to restrict the line-width of a laser to less than 1 kHz, useful for scientific applications. Some solid-state lasers have extremely broad bandwidths (order of hundreds of nanometers). This broad bandwidth enables the design of tunable and ultrafast (femtosecond and picosecond pulse width) lasers. Most applications of CW lasers require its stable power over long time (hours or weeks), as well as over short time durations (microseconds), depending on the specific application. To ensure this stability appropriate control of temperature and vibration, the aging of the laser itself and microprocessor control loops are very important factors [10, 11].

Pulsed lasers

Pulsed lasers are defined as laser devices that produce pulses of 0.5 to 500 ns (Figure 4). Some excited dimers (or "excimers") of a noble gas with halogen, such as ArF and XeCl, show quick laser action for only a several nanoseconds. Other lasers, like Nd or Yb diode-pumped solid-state (DPSS) lasers, also can operate both in CW or puls regime, while laser diodes, are not suitable at all for pulsed operations. The most important characteristic of a nanosecond-pulsed laser is the capability to "store" and release energy very rapidly; i.e., on a nanosecond scale so that the laser output can achieve tens of kilowatts to megawatts of peak power. This high-energy peak enables ablation of processing materials. Nanosecond-pulsed laser is substantially different from CW laser. The key to producing these energetic pulses is storing energy from the pump in atoms or molecules of the lasing medium by preventing the laser gain and the amplification process. Then, when the stored energy is at its maximum, lasing action is rapidly enabled [12].

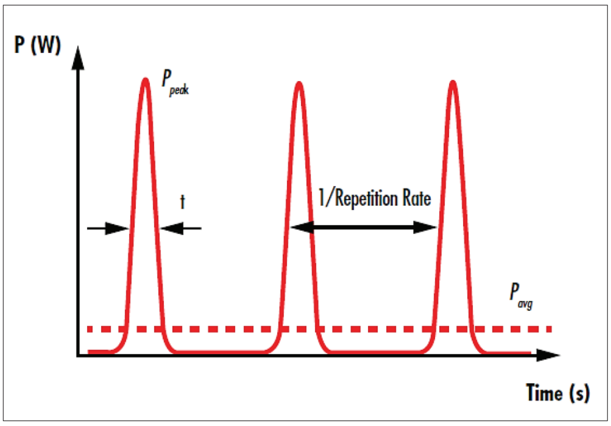

Figure 4. The pulses of a pulsed laser are temporally separated by the inverse of the repetition rate.

Slika 4. Pulsevi kod pulsnog lasera su privremeno razdvojeni inverzijom ponavljajuće frekvence.

The stored energy induces in extremely high laser amplification during only a few round trips, when giant pulse builds up. This regime is called Q-switched operation and can be presented as a two-mirror cavity with an optical gate located between one of the mirrors and laser medium. When the gate is closed and the laser medium is pumped, photons cannot circulate in the cavity, and the excitation of the atoms builds up, while when the gate is opened, photons start to build up via stimulated emission with a very large gain at each round trip. Typical pulse duration is 1 to 200 ns. It depends on the type of gain medium and how much energy it can store, the cavity length, the repetition rate of the pulses and the pump energy [13]. Excimer lasers do not require a Q-switch to produce nanosecond pulses, which are produced by exciting the noble gas-halogen mixture with powerful and short electric discharge.

Ultrafast lasers

Ultrafast lasers are lasers that produce pulses in the range of 5 fs to 100 ps (1 femtosecond = 10^{-15} seconds). Such short pulses can be produced with so-called mode-locking technique. With this technique, the modes are locked in phase (mode-locking regime) and their coherent interference causes the intra-cavity optical field to collapse into a single pulse traveling back and forth in the laser cavity. Generally, it is shown that as more as interfering modes, the pulse duration is shorter. Since larger lasing bandwidths support a larger number of oscillating modes, the pulse duration is inversely proportional to the bandwidth of the laser gain material. Ultrafast pulses are highly useful in research, due to short pulse duration and high peak power [14]. Recently developed femtosecond lasers enabled ground breaking research leading to Nobel prizes for femto-chemistry. Femtosecond lasers enabled multiphoton excitation (MPE) techniques that deliver three-dimensional imaging of live tissue. MPE is now widely used in several areas of biological research, presumably in neuroscience. In the case of femtosecond lasers, the high peak power of the amplified pulses can damage the laser optics. For this reason, the amplification is usually preceded by stretching the pulse (chirping) from 50 to 200 ps. The amplified pulse is then re-compressed to the fs domain. This is commonly referred to as chirped pulse amplification, or CPA (Figure 5).

In scientific research, amplified ultrafast pulses are used in photochemistry, pump-probe spectroscopy, terahertz (THz) generation and creating accelerated electrons and other small charged particles. The pulses can also drive nonlinear generation of extreme-UV light with pulse widths of tens of attoseconds [14, 15]. Ultrafast lasers are mainly based on titanium:sapphire (Ti:sapphire) because of its large bandwidth and broad tuning range, enabling them delivering pulses as short as 6 fs. Ti:sapphire lasers are typically pumped using a green-wavelength CW pump laser. Typical repetition rates of Ti:sapphire oscillators are 50 to 100 MHz, and peak powers several hundred kilowatts. The most common CPA systems based on Ti:sapphire operate at 1 to 10 kHz with the amplifier stages energized by nanosecond green lasers. It has ability to produce pulse

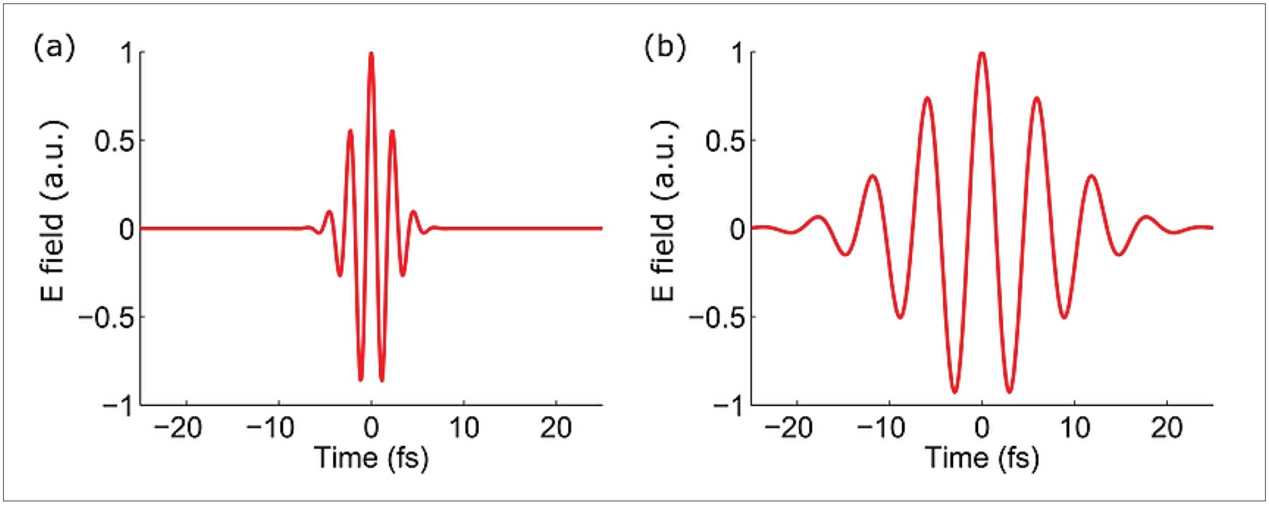

Figure 5. Calculated electric field evolution of the laser pulses used in experiment. (a) Pulse duration: 5 fs, central wavelength: 700 nm, (b) Pulse duration: 18 fs, central wavelength: 1800 nm

Slika 5. Izračunata evolucija električnog polja pulsa lasera tokom ogleda. (a) Trajanje pulsa: 5 fs, središnja talasna dužina: 700 nm, (b) Trajanje pulsa: 18 fs, središnja talasna dužina: 1800 nm.

energies of several milijoules with pulse widths as short as 20 fs. These systems can produce power of petawatt range [16]. Most of these systems recently are based on Nd-doped bulk materials (e.g., YAG or glass) or fiber, or a combination of the two, although smaller gain bandwidth of Nd limited the ps regime [17].

Yb-doped materials combine to some extent the advantages of Ti:sapphire scientific lasers and Nd-based industrial lasers. For scientific research, the gain bandwidth of Yb means oscillator pulses can be as short as 50 fs, which is more than adequate for many applications, particularly in MPE microscopy [18]. As for the scientific applications extremely short (>6 fs) pulse widths and/or high pulse energies are needed, Ti:sapphire remains the preferred gain material for such purposes. Femtosecond laser pulses have two advantages over picosecond pulses for materials processing. First, the material interaction involves many simultaneous photons and becomes reasonably wavelength insensitive, unlike with nanosecond linear absorption. Second, the short pulses and nonlinear interaction influence that fs pulses can deliver even better edge quality and precision than ps pulses.

Typical laser properties

The photons inside the laser beam are all in phase, or "coherent," causing propagation of electric field with a uniform wave front. Because a laser beam is highly directional, its brightness is much more intense than other light sources. An ideal laser should emit all photons with exactly the same energy and wavelength, and it would be perfectly monochromatic, but due to several broadening mechanisms as it is Doppler broadening frequently, frequency is often widened. Consequently, YAG lasers can have line widths of hundreds of gigahertz, while stabilized diode-pumped YAG lasers can have a line width <1 kHz [19].

Today, lasers enable for the first time DNA sequencing, and freezing the motion of electrons around atoms as it can generate very short pulses (below 10^{-16} s), and measurements of the absolute frequencies with an accuracy of ~10^{-15}. The input energy can take many forms. Among them, two most frequent are optical and electrical. For optical pumping, lamp or another laser as energy source are used, while for electrical pumping DC current (as in laser diodes) electrical discharge (noble gas lasers and excimer lasers), or a radio-frequency discharge (some CO_2 lasers) are used [20].

There are several kinds of lasers used in dental practice, which are divided according to active medium that is stimulated. This medium can be gas (e.g. argon, carbon dioxide), liquid (dyes) or solid state crystal rod as in the case of the neodymium yttrium aluminum garnet (Nd:YAG), erbium yttrium aluminum garnet (Er:YAG) or a semi conductors (diode lasers). As it was explained above the active mediums contain atoms which electrons can be excited to a metastable energy level by an energy source: optical (e.g. xenon flash lamps, other lasers), electrical (e.g. gas discharge tubes, electric current in semi-conductors) or chemical method. Due to the high level of coherency of monochromatic laser beam, its energy can be delivered on to target tissue as a continuous wave, gated-pulse mode (laser is periodically in an on and off mode) or free running pulse mode (energy is emitted for an extremely short span, in microseconds followed by a relatively long time which the laser is off). Fibre optics for visible and near infrared lasers is used for more efficient transfer energy to the corresponding tissue, while the articulated arms, with mirrors at joints, was used for UV, visible and infrared lasers, and hollow waveguides (flexible tube with reflecting internal surfaces), for middle and far infrared lasers [21].

Recently, fibre optic delivery systems are mostly used, as they can deliver laser energy to most parts of the oral cavity, even within the complex root canal system. This system can deliver energy in forward direction, with minimal dissipation from the bare end of a plain tip. Therefore, it is applied in cases of cavity preparation or soft tissue surgery. In some cases, this drawback related to the energy dissipation may cause some difficulties in lateral transfer energy, limiting its use for applications in root canal treatment. Recently, a number of fibre optic modifications are suggested to overcome this limitation. Other factors that influence the laser choice for dental hard and soft tissue are absorption of laser beam by chromophores (water, apatite minerals, and various pigmented substances) inside of the target tissue because better absorption allows more efficient photo-thermal sterilization, ablation of dentin, etc. Besides, rapid heating of water molecules within enamel can cause rapid vaporization of water and build-up of steam that induce huge expansion of dental structures, leading to material breaks by exploding, through this process of ablation. In the case of high-powered lasers, tissue vaporization or coagulation through absorption in a major tissue component is known as photo-thermal ablation. Photomechanical ablation includes tissue disruption due to shock wave formation, cavitation, etc. The photochemical effects are induced by light-sensitive substances, and today are used for its antibacterial effect and in cancer treatment. The typical variables in laser application are wavelength, pulse energy or power output, exposure time, spot size (and thus energy density), and the tissue physical and chemical composition (e.g. water content, density, thermal conductivity and thermal relaxation) [22].

Lasers are grouped into seven classes depending on the potential for the beam to cause harm. The hazard and classification depend on the wavelength, power, energy and pulse characteristics. These groups are: class 1 and 1M (inherently safe); class 2 and 2M (where the eye is protected by the blink reflex); class 3R and 2B (where direct viewing is hazardous); and class 4 (where the laser power is above 0.5 Watts, and the laser is classed as extremely hazardous) [23].

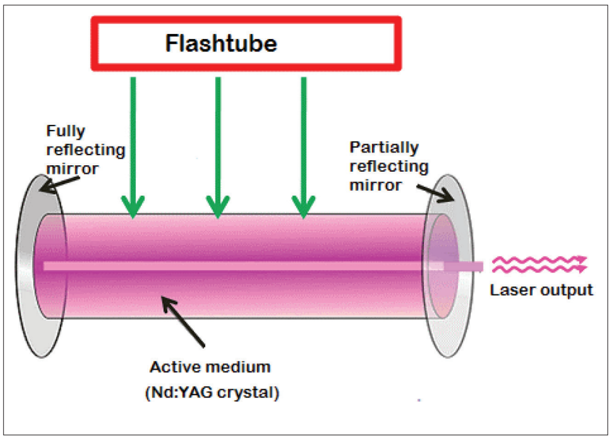

Figure 6. Typical schematic appearance of Nd: YAG laser
Slika 6. Tipični šematski prikaz lasera Nd:YAG

Dental lasers

Most dental and medical lasers belong to class IV, and thus, compliance with safety standards is necessary to protect the dentist, patient and supporting staff. Lasers used in dentistry vary from ultraviolet light (100-400 nm), to infrared spectrum (750 nm-1 mm). The visible spectrum lies between these two wavelengths (400-750 nm). Lasers used in dentistry cover a broad range of procedures, from diagnosis of caries or cancer to soft tissue and hard tissue procedure.

The first application of laser on dental tissue was reported by Goldman et al. and Stern and Sognnaes, when the effects of the ruby laser on enamel and dentin were described [3, 4]. Many studies were done after 1985, after publishing the paper by Myers that described *in vivo* removal of dental caries using modified ophthalmic Nd:YAG laser (Figure 6) [5]. Four years later, Nd:YAG laser (neodymium doped yttrium aluminum garnet) was used for oral soft tissue surgery, and that introduced the use of these lasers in clinical periodontics [24]. Lasers commonly used in dentistry consist of a variety of wavelengths delivered as either a continuous, pulsed (gated), or running pulse waveform, e.g., CO_2, Nd:YAG, Ho:YAG, Er:YAG, Er, Cr:YSGG, Nd:YAP, GaAs, diode laser and argon laser (Figure 7). Lasers with shorter wavelengths and pulse widths combined with higher-power densities are not currently relevant to dental applications [25].

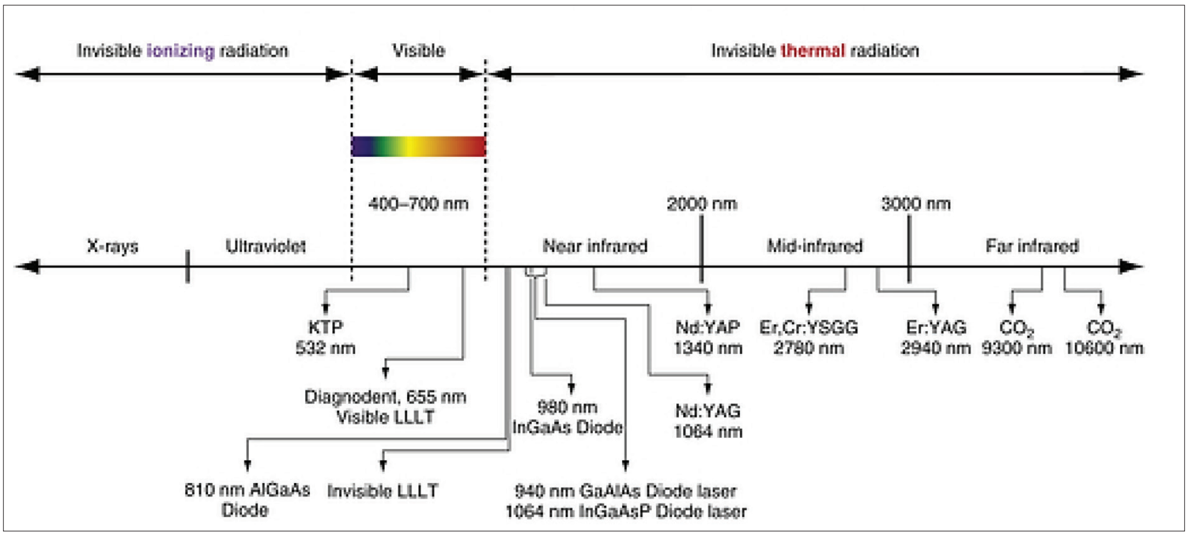

Figure 7. Dental lasers wavelengths in the electromagnetic spectrum
Slika 7. Laseri u stomatologiji po talasnim dužinama prema elektromagnetnom spektru

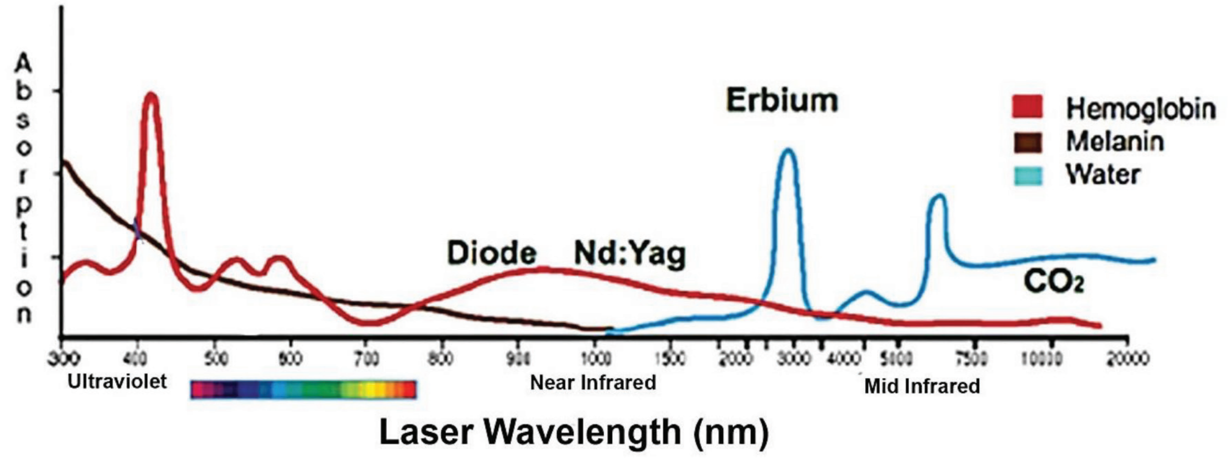

Figure 8. Lasers used in dentistry and their affinity to oral materials
Slika 8. Laseri primenjeni u stomatologiji i njihov afinitet ka oralnim tkivima

In biologic tissues, the laser energy is absorbed by surface tissues and will only exhibit scattered penetration in deep tissues. Absorbed light energy is converted to heat and cause various photo thermal events like warming, coagulation, or excision and incision through tissue vaporization. The energy absorption depends on various parameters like emission wavelength, power (watts), waveform (continuous or pulsed), pulse duration, energy/pulse, energy density, duration of exposure, peak power of pulse, angulation of the energy delivery tip to the target surface, and optical properties of the tissue (Figure 8) [26].

Optical properties of a tissue influence the interaction with specific laser wavelengths. In the case of periodontium, optical properties of tissues depend on its pigmentation, water content, mineral content, heat capacity that accounts for both thermal conductivity and tissue density, and latent heat transformation (i.e., denaturation of proteins, vaporization of water, and melting of mineral). Taking into account that bone is the classic composite tissue, consisting of 67% inorganic minerals (calcium hydroxyapatite) and 33% collagen and non-collagenous proteins, or gingiva which is constituted from various densities of fibrous connective tissue, associated extracellular matrix components, and a high content of water (70%), their optical properties are also determined by its specific composition. Additionally, gingiva frequently exhibits melanin pigmentation. Other factors that are included in laser-tissue interactions are processes of heat conduction and dissipation, the degree of tissue inflammation and vascularity, and availability of progenitor cells to participate in the healing process. Each wavelength of laser energy is absorbed to a greater or lesser degree in their components, like water, pigment, or hydroxyapatite [27].

Knowing that CO_2 laser (10600 nm wavelength) has a high absorption coefficient in water, it is suitable for soft tissue surgery but recently it has no scientifically well-supported clinical application to mineralized tissues. Nd:YAG (1064 nm wavelength) and diode lasers (800 to 950 nm wavelength) have lower absorption coefficients in water than CO_2 lasers, but they are preferentially absorbed in pigmented tissues, while the Er,Cr:YSGG and Er:YAG wavelengths (2780 and 2940 nm, respectively) are highly absorbed in both water and hydroxyapatite [28]. Therefore, the clinicians should, in each case, determine the specific clinical treatment aims and then select the adequate technology (laser or otherwise) to achieve the desired endpoint(s).

For many intraoral soft tissue surgical procedures, the laser is suitable alternative to scalpel. The CO_2, Nd:YAG, and diode lasers are primarily used for intraoral soft tissue procedures, such as frenectomy, gingivectomy and gingivoplasty, epithelization of reflected periodontal flaps, removal of granulation tissue, second stage exposure of dental implants, lesion ablation, incisional and excisional biopsies of both benign and malignant lesions, irradiation of aphthous ulcers, coagulation of free gingival graft donor sites, and gingival depigmentation. Besides, there are evidences of faster healing after using laser on soft tissue wounds that are wavelength specific and highly sensitive to energy density. Most studies used CO_2, Nd:YAG, or diode lasers. A comparison of wound healing induced by Nd:YAG and CO_2 lasers indicates that CO_2 laser used in oral, oropharyngeal and laryngeal mucosa caused significantly faster healing than Nd:YAG laser, but conventional scalpel-induced wound healed faster then after laser use. Wound healing was comparable between scalpel and Nd:YAG laser when laser was used at lower power of 1.75 W and 20 Hz. However, investigations based on tissue histology showed that high power (watts), long pulse duration, high repetition rates (hertz), and long interaction times (duration of target exposure) all increased the risk of negative outcomes. Comparison of laser and scalpel surgery was broadly investigated in numerous medical and veterinary journals. From the aspect of laser wavelengths and various tissue parameters like incision time, blood loss, swelling and oedema, pain, and general wound healing, great diversity of data has been reported. However, in most papers laser technology showed numerous advantages, like higher level of clinician control, operating efficiency, tip flexibility and accessory selection [27, 28].

Figure 9. Representative radiological images of tibia bone after artificial fracture
Slika 9. Reprezentativni rendgenski snimci tibije posle preloma

Effect of lasers on bone healing

Laser-biologic tissue interactions are wavelength dependent photo-thermal events, as most of dental laser effects on bone are potentially damaging. It seems that only wavelengths of Er:YAG and Er,Cr:YSGG lasers are suitable for such application. It has been shown that bone surface exposed to the same total laser energy showed temperature increase for CO_2 from 1.4^0C to 2.1^0C and for Nd:YAG laser, it was 8.0^0C to 11.1^0C [29, 30]. These results indicate that for ablation relatively thin soft tissues supported by adjacent bone is needed (e.g. mandibular facial, gingival and alveolar mucosa). If the Nd:YAG laser is used it should have relatively low energy densities emitted in short time intervals to prevent risk of irreversible bone damage. It was found that Er:YAG laser, when used at a peak pulse energy of 100 mJ/pulse and 10 Hz, produced well-defined intrabony cuts with no evidence of melting or carbonization [29–32]. Figure 9 shows that laser-treated group exhibited earlier new bone formation compared to non treated group [33].

Fourier transform infrared spectroscopy (FTIR), energy dispersive x-ray spectroscopy (EDX), and x-ray diffraction analysis revealed normal collagen/hydroxyapatite relationship with thin surface layer characterized by slight increase in calcium/phosphate ratio due to formation of tetracalcium phosphate, which was similar chemical composition formed after the use of rotary bur method. On the other hand CO_2 laser–induced osteotomies exhibited extensive carbonization, melting of mineral phase, and delayed healing [29]. Also, some recent studies suggested that Er, Cr:YSGG wavelength is suitable for use on bone, as EDX analysis showed no change in calcium/phosphate ratio, and there was no evidence of charring or melting. Surface modification of cement and dentin exposed to variety of laser wavelengths, primarily CO_2, Nd:YAG, and Er:YAG lasers showed that they can be efficiently used for removing calculus, if wavelength characterized by minimal penetration depth in mineralized tissue was selected. This is important to suppress both thermal damage to the pulp tissue and undesired removal of sound root structure. The mineral phase of both cement and dentin is carbonated hydroxyapatite that has intense absorption bands in the mid-infrared region [27–32].

Consequently, of all lasers studied, the Er:YAG laser would appear to be the laser of choice for effective removal of calculus, root etching, and creation of a biocompatible surface for cells and tissue reattachment. Contrary, if CO_2 laser it used, even at the low energy, FTIR analysis showed presence of toxic chemical residues of cyanamide and cyanate, followed by lack of flap reattachment to the surface of treated root area. Therefore, CO_2 lasers have restricted application in subgingival periodontal therapy. At energy densities of 100 to 400 J/cm^2 for CO_2 and 286 to 1,857 J/cm^2 for Nd:YAG lasers, the certain degree of morphologic change in root surfaces induced by laser irradiation, like cavitation defects, globules of melted and re-solidified mineral, changes in root structure proteins, surface crazing, and production of superficial layer directly dependent on energy density is observed. In contrast to studies reporting unfavourable results, Nd:YAG laser with low energy densities or combination of low energy density with a defocused beam, showed to be suitable for removing root surface smear layers without causing collateral damage to underlying cement and/or dentin, or increasing temperatures to a level that might trigger irreversible pulpal damage [34, 35, 36].

A relatively new laser, Nd:YAP with a wavelength of 1,340 nm, tested on root surfaces of extracted teeth, showed the presence of heat-induced damages at energy densities ranging from 509 to 1,274 J/cm^2. The degree of damage was directly related to increasing energy density and progressively grew from simple surface cracking of cement to deep cratering, melting and deep ablation of cement with exposure of underlying dentin. Recently, the Er,Cr:YSGG laser, and to a lesser extent the Er:YAG laser, have been promoted for clinical crown lengthening without gingival flap reflection for both aesthetic and prosthetic reasons. Obviously, aesthetic crown lengthening can easily be managed with lasers if clinically short crowns are the result of gingival overgrowth or lack of passive eruption. In such cases increased probing depth (PD) is caused by excessive amounts of soft tissue [34–37].

The use of dental laser in the treatment of chronic periodontitis is based on regeneration of mucogingival attachment, cement, periodontal ligament, and supporting alveolar bone, and significant decrease in sub-gingival pathogenic bacteria. There is limited evidence suggesting that lasers cause greater reductions in subgingival bacteria than that achieved by traditional treatment. Most laser bactericidal studies report a dose/response relationship. However, in many studies, energy densities are often not reported or cannot be calculated due to incomplete listing of parameters. Finally, the angle of irradiation can vary from 0 to 90^0, making computation of energy densities nearly impossible [38–41].

One of the first *in vivo* studies reporting reductions in pathogenic bacteria following irradiation with Nd:YAG laser showed decrease in *Porphyromonas gingivalis* (Pg), Prevotella *intermedia* (Pi) and *Actinobacillus actinomycetemcomitans* (Aa) [38]. However, teeth extracted 7-days post-treatment exhibited recolonization of laser-irradiated subgingival root surfaces by multiple morphotypes of bacteria. *In vitro* studies using Nd:YAG laser at low power settings have reported calculus ablation without detrimental effects to underlying cement or dentin. A linear relationship between energy level, microbial numbers, and concentration of hemoglobin (blood) has been found as well as minimal energy required for bactericidal effect, different susceptibility of various microbes to laser energy, different susceptibility to damage of calculus, cement, and dentin, even within the same specimen. It also showed variability in color, thickness, composition, texture, and water content [38–41]. The diode laser (805 nm), when used adjunctively with traditional scaling and root planning method (SRP), have shown an additive effect in reducing subgingival bacterial populations in periodontal pockets of 4 mm depth. However, many *in vivo* studies showed the persistence of viable bacteria following subgingival laser irradiation [38, 40, 41].

CONCLUSIONS

In this paper irradiation of biologic tissues by a specific wavelength of laser was studied. Based on this review, interaction of dental tissue with laser depends on the type, energy and wavelength of lasers used. This knowledge should be implemented for the right choice of laser parameters, without destruction of treated soft and hard dental tissues. Beside specific laser applications, our review described basic elements of stimulated emission; principles of laser function, main types of laser instrumentation, advantages and disadvantages of certain types of laser applications.

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Primena lasera u stomatologiji – pregled literature

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KRATAK SADRŽAJ

U ovom radu opisan je mehanizam stimulisane emisije, kao osnova tehnologije rada lasera. Navedeni su i tipovi lasera sa aspekta njihove primene. Posebna pažnja je posvećena laserima u stomatologiji, kao i uticaju njihovih karakteristika na mogućnost regeneracije kosti, dentina i drugih oralnih tkiva.

Ključne reči: laseri; laseri u stomatologiji; regeneracija kosti; čvsto zubno tkivo; meko tkivo

UVOD

Na osnovu teorije o spontanoj i stimulisanoj emisiji zračenja Alberta Ajnštajna, Majman je napravio prvi prototip lasera 1960. godine [1]. Njegov uređaj je koristio kristalni medijum rubina, koji je emitovao koherentno svetlo kada je bilo stimulisano energijom. Nešto kasnije, 1961. godine, Šnicer je objavio rad koji je opisivao prototip lasera Nd:YAG [2]. Prva primena lasera na oralnim tkivima opisana je od strane Goldmana i sar., kao i Sterna i Sognesa [3, 4]. Opisana je primena rubinskog lasera u nagrizanju gleđi i dentina. Dalja primena lasera u stomatologiji zabeležena je u radu publikovanom 1985. od strane Majersa i Majersa, u kome je prikazano *in vivo* uklanjanje zubnog karijesa korišćenjem modifikovanog oftalmološkog lasera Nd:YAG [5]. Nekoliko godina kasnije preporučena je upotreba lasera Nd:YAG u mekotkivnoj hirurgiji za lečenje mnogobrojnih oralnih oboljenja [6].

Cilj ovog preglednog rada je analiza veoma širokog polja primene lasera i principa njihovog funkcionisanja, u nameri da se da kratki pregled današnjih stavova u stomatološkim naukama u vezi sa primenom lasera na tvrdim i mekim oralnim tkivima.

Osnovna teorija lasera

Laser je akronim nastao od engleskih reči za amplifikaciju svetla stimulisanom emisijom zračenja (eng. *Light Amplification by Stimulated Emission of Radiation*). Laseri su u svom razvoju prošli veliki put od kad je Albert Ajnštajn opisao teoriju stimulisane emisije 1917. godine. Ajnštajn je u svojoj teoriji predvideo da pobuđeni atomi mogu pretvoriti nastalu energiju u svetlost tokom procesa u kome foton određene frekvencije interaguje sa pobuđenim elektronom (ili nekim drugim pobuđenim molekularnim stanjem), dovodeći do smanjenja nivoa energije atoma. Energija/foton nastala pri tome prenosi se u elektromagnetnom polju stvarajući novi foton. Ovaj proces ima dva važna svojstva. Prvi je svojstvo mutliplikacije, jer jedan foton indukuje stvaranje dva fotona. Ukoliko ova dva fotona dođu u interakciju sa druga dva pobuđena atoma, kao rezultat će nastati četiri fotona, i tako dalje (Slika 1). Drugo, veoma važno svojstvo je to što nastali fotoni imaju identične karakteristike: talasnu dužinu, usmerenost, fazu i polarizaciju. Ovo svojstvo „umnožavanja“ svetla u prisustvu dovoljnog broja pobuđenih atoma vodi u „optičku dobit“, koja je osnova funkcionisanja lasera [7].

Slika 2 prikazuje lasere sa tri i četiri nivoa energije (a, b). Kod lasera sa tri nivoa snop energije pobuđuje elektrone u preko pola atoma i prevodi ih iz osnovnog u više stanje, stvarajući inverznu populaciju elektrona. Elektroni se zatim spuštaju u dugopostojeće stanje sa nešto nižom energijom, iz koga lako mogu biti stimulisani da brzo oslobode višak energije u vidu laserskog snopa, vraćajući elektron u stabilno osnovno stanje. Kod lasera sa četiri nivoa energije kontinuiran laserski zrak može se postići primenom atoma koji imaju dva relativno stabilna stanja između osnovnog i visokoenergetskog pobuđenog stanja. Kao kod lasera sa tri nivoa energije, atomi prvo prelaze u dugopostojeće međustanje, u kom mogu biti stimulisani da emituju višak energije. Međutim, oni se umesto prelaska u osnovno stanje zadržavaju u stanju iznad osnovog, iz kog lakše mogu biti pobuđeni nazad u međuenergetsko stanje, tako održavajući inverziju populacije potrebnu za kotinuirani rad lasera.

Otkriven je veliki broj materijala u čvrstom, tečnom i gasovitom stanju koji mogu ući u stanje pobuđenosti pod dejstvom odgovarajućeg snopa energije. Laser se obično sastoji od rezonatora (laserskog kućišta), u kom lasersko zračenje može da se prostire i prolazi kroz ciljani medijum, čime se kompenzuje optički gubitak (Slika 3). Izuzetak predstavljaju pojedini slučajevi u kojima se koristi medijum visoke energije, tako da umnožena spontana emisija oslobađa veliku energiju u jednom prolazu kroz ciljani medijum, kao što je slučaj sa egzajmer laserima. Pored toga, rezonator obično sadrži u sebi sistem ogledala, omogućavajući višestruki prolaz stvorenih fotona kroz ciljani medijum, i dodatne optičke elemente, odnosno elemente za podešavanja talasne dužine, Q prelazni mod ili zaključavanje. Laserski medijumi su kristali, poluprovodnici, ili gasovi smešteni u odgovarajuću zatvorenu strukturu. Smešteni su duž optičke osovine rezonatora. Ova jedinstvena osovina sa visokim nivoom optičke energije postaje pravac širenja laserskog svetla. Nešto drugačiji primer jedinstvene, duge (ili savitljive) energetske osovine nalazi se u vlaknu lasera [8, 9].

Vrste lasera

Laseri se, sa aspekta rada, mogu podeliti u tri osnovne kategorije: laseri u kontinuiranom (neprekidnom) radu (CW), pulsni i ultrabrzi pulsni.

Kontinualni mod lasera

Kontinualni talasni laseri proizvode kontinualni, neprekidni laserski zrak, uz veoma stabilnu izlaznu snagu. Tačna talasna dužina laserskog snopa je određena karakteristikama laserskog medijuma. Na primer, CO_2 molekuli ekscituju zrak na 10,6 μm, dok kristali zasnovani na neodimijumskim kristalima (kao što je YAG ili vanadati) produkuju zrak talasnih dužina između 1047 i 1064 nm. Dodatno, svaka talasna dužina praćena je odgovarajućim promerom, koji uglavnom zavisi od protoka kroz medijum, filtera i dizajna optičkog rezonatora. Specifična talasna dužina izlaznog zraka u okviru datog frekventnog opsega određena je longitudinalnim modovima kutije. Laseri koji produkuju višestruke longitudinalne modove imaju ograničenu koherentnost, jer različite talasne dužine ne mogu ostati u fazi tokom velikih rastojanja [10].

Za neke tipove lasera sa uzanim poljem frekventnog opsega, pojedinačni izlazni mod je postignut uz veoma kratku rezonantnu kutiju. Uopšteno, filtrirajući elementi se koriste kako bi se omogućio prolaz samo željenog moda u kutiju. Najčešći tip filtera naziva se etalon. Koristeći različite sofisticirane dizajne pojačivača, moguće je ograničiti promer snopa lasera na manje od 1 kHz, što je korisno za naučnu primenu. Pojedini laseri sa medijumom u čvrstom stanju imaju izrazito široke opsege (izražene u stotinama nanometara).

Široka polja frekventnog opsega omogućavaju dizajn izrazito brzih pulsnih lasera (pauze između pulsa izražene su u femtosekundama i pikosekundama). Primena kontinuiranih lasera zahteva stabilnu snagu tokom dužeg perioda vremena (sati ili nedelje), kao i tokom kraćih perioda (mikrosekunde), zavisno od primene. Kako bi se osigurala adekvatna kontrola temperature i vibracija, vreme starenja samog lasera i mikroprocesora su veoma bitni faktori [10, 11].

Pulsni mod lasera

Pulsni laseri su definisani kao uređaji koji produkuju pulseve između 0,5 do 500 ns (Slika 4). Pojedini ekscitovani dimeri (ekscimeri) plemenitih gasova sa halogenom, kao što su ArF i XeCl, omogućuju veoma brzo dejstvo lasera, koje odgovara vremenu od samo nekoliko nanosekundi. Drugi laseri, kao Nd ili Yb diodni pumpani laseri čvrstog stanja (DPSS), mogu raditi i u kontinualnom i pulsnom modu, dok diodni laseri nisu pogodni za sve pulsne operacije. Najvažnija karakteristika nanosekundnih pulsnih lasera je sposobnost da skladište i oslobode energiju vrlo brzo, pri čemu na nanosekundnoj skali izlazna snaga lasera može postići reda desetine kilovata do megavata snage. Ovaj pik visoke energije omogućava ablaciju materijala, kada se laser koristi u proizvodnji. Nanosekundni pulsni laseri značajno su drugačiji od lasera koji rade u kontinualnom modu. Ključ proizvodnje energetskih pulseva leži u uskladištenoj energiji pumpenjem atoma ili molekula medijuma, što doprinosi aktivnosti lasera i pojačava/ amplifikuje proces prenosa energije. Pritom, kada je skladištena energija na maksimumu, omogućeno je brzo dejstvo lasera [12].

Skladištena energija uslovljava ekstremno velika laserska pojačanja tokom nekoliko ponavljanja, u kojima se proizvodi gigantski puls. Ovaj režim podrazumeva primenu Q-prekidača, koji je smešten u šupljini sa dva ogledala i optičkim izlazom, radi pumpanja energije, koji vodi ka laserskom medijumu. Kada je izlaz zatvoren, fotoni ne cirkulišu u kutiji, te ekscitacija atoma raste, dok posle otvaranja izlaznog dela nastaju fotoni stimulisanom emisijom uz veliku koncentraciju tokom svakog ciklusa. Standardno trajanje pulsa iznosi od 1 do 200 ns. Ono zavisi od vrste medijuma i količine sačuvane energije, dužine kutije, ponavljanja pulsnih talasa i energije [13]. Ekcimer laseri ne zahtevaju Q-prekidače da bi produkovali nanosekundne pulseve, koji u ovom slučaju nastaju ekscitacijom mešavine plemenitog gasa i halogena, koji poseduje moćna kratka električna pražnjenja.

Ultrabrzi laseri

Ultrabrzi laseri produkuju pulseve u rangu između 5 fs do 100 ps (1 femtosekund = 10^{-15} sekundi). Tako kratki pulsevi mogu se razviti tokom takozvane tehnike zaključavanja moda. Tokom ove tehnike modovi su zaključani u fazi (režim zaključanog moda) i njihova koherentna interferencija prouzrokuje da unutar kutije kolapsira optičko polje u jedinstveni puls koji se kreće nazad-napred u kutiji. Pokazano je da što je više interferentnih modova puls je kraći. Pošto veća širina frekventnog opsega podstiče veći broj oscilirajućih modova, dužina pulsa je obrnuto proporcionalna širini frekventnog opsega medijuma lasera. Ultrabrzi laseri su veoma korisni u istraživanjima zbog svojstava kratkog trajanja pulsa i postizanja visokih snaga [14]. Nedavno razvijen femtosekundni laser za koji je dobijena Nobelova nagrada u oblasti hemije omogućio je veoma značajna istraživanja u oblasti medicine. Femtosekundni laseri omogućavaju tehnike multifotonske ekscitacije, koje dalje daju trodimenzionalne slike živih tkiva. Tehnika multifotonske ekscitacije je danas široko primenjena u nekoliko oblasti bioloških istraživanja, posebno u neuronauci. U slučaju femtosekundnih lasera, visoki pik snage umnoženih pulseva može oštetiti optički sistem lasera. Usled toga, umnožavanje je obično praćeno produžavanjem pulsa (pojačanje) od 50 do 200 ps. Umnoženi puls se zatim rekompresuje u fs domen, što se naziva pojačanje pulsiranog impulsa (CPA) (Slika 5).

U istraživanjima, umnoženi ultrabrzi pulsevi se primenjuju u fotohemiji, spektroskopiji, terahercnoj generaciji ubrzanih elektrona i ostalih naelektrisanih čestica. Pulsevi mogu dovesti i do nastanka nelinearnog ekstremnog UV zračenja uz trajanje pulsa od nekoliko desetina atosekundi [14, 15].

Ultrabrzi laseri su uglavnom bazirani na titanijum:safiru (Ti:safir) zahvaljujući velikoj širini frekventnog opsega i opsegu podešavanja frekvencije, što omogućava produkovanje kratkog pulsa dužine 6 fs. Laseri Ti:safir su obično povezani sa laserima koji pripadaju opsegu frekvencija zelenog svetla u kontinuiranom modu rada. Prosečno ponavljanje oscilatora Ti:safir iznosi od 50 do 100 MHz, dok se najveće snage mere u stotinama kilovata. Najčešći CPA sistemi su zasnovani na radu lasera Ti:safir pri 1 do 10 kHz uz nanosekundni zeleni laser za amplifikaciju energije. Može da produkuje pulsne energije od nekoliko milidžula uz trajanje pulsa od samo 20 fs. Ovi sistemi mogu produkovati snagu u rangu veličine petavata [16].

U poslednje vreme većina ovih sistema zasnovana je na Nd-dopiranim materijalima (YAG ili staklo) ili vlaknu, ili kombinaciji ova dva, mada se niža širina frekventnog opsega Nd ograničava na pikosekundni režim [17].

Yb-dopirani materijali kombinuju određene prednosti Ti:safira primenjenih u naučnim istraživanjima i Nd-dopiranih materijala, koji se najčešće koriste u industriji. Za naučna istraživanja širina frekventnog opsega pulsa Yb oscilatora može iznositi samo 50 fs, što je više nego pogodno za razne primene, posebno u MPE mikroskopiji [18]. Usled potrebe da se u istraživanjima primenjuju ekstremno kratki (> 6 fs) pulsevi velikih energija, Ti:safir ostaje najpoželjniji laserski medij/material u ovoj oblasti istraživanja.

Femtosekundne pulsne lasere karakterišu dve prednosti u odnosu na pikosekundne lasere za obradu materijala. Prvo, interakcija materijala podrazumeva mnoge simultane fotone, te materijal postaje neosetljiv na talasnu dužinu, za razliku od nanosekundne linearne apsorpcije. Drugo, kratki pulsevi i nelinearna interakcija utiču da fs pulsevi mogu biti kvalitetniji i precizniji od ps pulseva.

Osnovne karakteristike lasera

Fotoni u laserskom svetlu su svi u fazi, odnosno koherentni, prouzrokujući prolaz električnog polja sa uniformnim talasnim frontom. Usled velike usmerenosti laserskog zraka, jačina svetla je značajno intenzivnija u odnosu na druge izvore svetlosti. Idealni laser trebalo bi da emituje sve fotone potpuno iste energije i talasne dužine, koji bi bili savršeno monohromatski, ali usled nekoliko mehanizama širenja, kao što je Dopler efekat, frekvenca je proširena. Posledično, laseri YAG mogu imati širine od nekoliko stotina gigaherca, dok laseri YAG stabilizovani diodnom nadogradnjom mogu imati širinu <1 kHz [19].

Danas, laseri prvi put omogućavaju sekvenciranje DNK molekula, „zamrzavanje“ elektrona u pokretu oko atoma usled mogućnosti produkovanja veoma kratkih pulseva (ispod 10^{-16} s), kao i merenja apsolutnih frekvencija sa tačnošću od $\sim 10^{-15}$. Primljena energija može uzeti mnoge oblike. Među njima, dva najznačajnija su optički i električni izbor energije. Kao optički izvor energije koristi se lampa ili drugi laser, dok se kao električni izvor koristi DC struja (kao u diodnim laserima), električno pražnjenje (laseri plemenitih gasova i egzajmer laseri), ili radiofrekventno pražnjenje (pojedini CO_2 laseri) [20].

Nekoliko vrsta lasera se primenjuje u stomatologiji, a dele se prema aktivnom medijumu koji je stimulisan. Medijumi mogu biti gasovi (argon, ugljen-dioksid), tečnost (neke organske boje), čvrsto kristalno stanje (Nd:YAG, Er:YAG) i poluprovodnici (diodni laseri). Kao što je ranije objašnjeno, aktivni medijumi sadrže atome čiji elektroni mogu biti ekscitovani do metastabilnog nivoa energije primenom različitih energetskih izvora: optičkih (ksenon lampe, drugi laseri), električnih (električno pražnjenje, električna struja u poluprovodnicima) ili hemijskih. Usled visokog nivoa koherentnosti monohromatskog laserskog svetla energija može biti isporučena do ciljanog tkiva u vidu kontinuiranog talasa, u pulsnom modu (laser je periodično u modu uključeno-isključeno), ili slobodnom pulsnom modu (energija je emitovana u veoma kratkom periodu, u mikrosekundama, praćena relativno dugim periodom u kome je laser neaktivan). Za zrak iz vidljivog spektra i lasere koji rade u opsegu bliskog infracrvenog spektra koriste se optička vlakna za efikasniji prenos energije do ciljanog tkiva, dok se uzglobljeni nastavci sa ogledalima i spojevima koriste za lasere sa UV, vidiljivim i infracrvenim spektrima laserskog zraka, dok se šuplji provodnik radiotalasa (savitljiva cev sa refleksivnom unutrašnjom površinom) koristi za lasere iz srednjeg spektra i spektra udaljenog od infracrvenog [21].

U poslednje vreme se najčešće koriste optička valkna jer mogu dostaviti energiju lasera do većine oralnih tkiva, čak i u kompleksni kanalni sistem korena zuba. Optički sistem isporučuje energiju sa distalnog kraja nastavka u usmerenom zraku uz minimalno bočno rasipanje. Stoga se primenjuje u preparaciji kaviteta ili mekotkivnoj hirurgiji. U određenim slučajevima nedostatak koji proizilazi iz minimalnog bočnog rasipanja energije može dovesti do poteškoća tokom bočnog prenosa energije, što ograničava primenu u endodontskom tretmanu. Nedavno su predložene različite modifikacije optičkog vlakna kako bi se prevazišli pomenuti nedostaci. Ostali faktori koji utiču na odabir lasera za rad na tvrdim i mekim oralnim tkivima su apsorpcija laserskog zraka od strane tkivnih hromofora (voda, apatit, pigmenti) u ciljanom tkivu, jer je bolja apsorpcija praćena efikasnijom fototermalnom sterilizacijom, ablacijom dentina, i ostalim dejstvima. Pored toga, brzo zagrevanje molekula vode u gleđi može uzrokovati vaporizaciju vode i stvaranja pare, što izaziva brzo širenje dentalnih tkiva, te vodi do minieksplozija u tkivu kroz process ablacije. U slučaju lasera velike snage, vaporizacija ili koagulacija tkiva kroz apsorpciju energije u tkivnim komponentama naziva se i fototermalna ablacija. Fotomehanička ablacija podrazumeva ukanjanje tkiva posredstvom stvaranja šok talasa, kavitacije. Fotohemijsko dejstvo nastaje posredstvom supstanci osetljivih na svetlo, i danas se primenjuje u antibakterijskom dejstvu i lečenju kancera. Indikacije za primenu lasera najčešće zavise od talasne dužine, pulsne energije i izlazne snage, vremena izlaganja, površine dejstva (samim tim i gustine energije), i tkivnog fizičkog i hemijskog sastava (sadržaja vode, gustine, toplotne provodljivosti i vremena oslobađanja od stvorene toplote) [22].

Svi laseri su grupisani u sedam klasa zavisno od potencijala izlaznog zraka da uzrokuje povredu. Oštećenje, i stoga i klasifikacija, zavise od talasne dužine, snage, energije i karakteristika pulsa. Laseri su grupisani u: klasu 1 i 1M (nizak nivo mogućnosti oštećenja), klasu 2 i 2M (oči mogu da se zaštite od zraka refleksom treptanja), klasa 3, 3R i 2B (direktno gledanje u zrak može dovesti do oštećenja), i klasa 4 (snaga lasera je iznad 0,5 vati i laser je klasifikovan kao izrazito štetan) [23].

Laseri u stomatologiji

Većina lasera u stomatologiji i medicini pripadaju klasi 4 i stoga je neohodno sprovesti standarde adekvatne zaštite da bi se zaštitili stomatolog, pacijent i pomoćno osoblje. Laseri u stomatologiji variraju od ultravioletnog svetla (100–400 nm) do infracrvenog spektra (750 nm – 1 mm). Vidljivi spektar se nalazi između dve talasne dužine (400–750 nm). Laseri se u stomatologiji primenjuju pri raznim procedurama, od dijagnoze karijesa ili kancera do mekotkivnih i procedura na tvrdim zubnim tkivima.

Goldman i sar. i Stern i Sognas su prvi opisali primenu lasera na oralnim tkivima, gde je rubi laserom delovano na tkiva gleđi i dentina [3, 4]. Naredna ekspanzija istraživanja iz ove oblasti desila se 1985. godine, posle publikacije Majersa, u kojoj je opisano *in vivo* uklanjanje zubnog karijesa primenom modifikovanog lasera Nd:YAG za primenu u oftalmologiji (Slika 6) [5]. Četiri godine kasnije laser Nd:YAG je primenjen u oralnoj hirurgiji na mekom tkivu, što je uticalo na dalja istraživanja primene ovog lasera u kliničkom lečenju parodontopatija [24]. Laseri u stomatologiji danas odlikuju se različitim talasnim dužinama i dejstvom zraka u kontinuiranom, pulsnom modu sa vratima i slobodnom pulsnom modu, odnosno primenjuju se CO_2, Nd:YAG, Ho:YAG, Er:YAG, Er, Cr:YSGG, Nd:YAP, GaAs, diodni laseri i argonski laseri (Slika 7). Laseri kraćih talasnih dužina i pulsnog opsega kombinovani sa gustinama velikih snaga trenutno nisu od interesa za primenu u stomatologiji [25].

U slučaju bioloških tkiva, energija lasera je apsorbovana na površini tkiva izloženom laseru i u slučaju dubljeg prolaska zraka dolazi do ožiljavanja. Apsorbovana energija se prevodi u toplotu i izaziva različite fototermalne efekte kao što su zagrevanje, koagulacija, ekscizija i incizija tokom vaporizacije tkiva. Apsorpcija energije zavisi od talasne dužine zraka, snage, moda rada (kontinuirani ili pulsni), dužine trajanja pulsa, odnosa energija/puls, gustine energije, dužine izlaganja, najvećeg pika snage pulsa, angulacije distalnog kraja optičkog vlakna u odnosu na tkivo, kao i optičkih svojstava tkiva (Slika 8) [26].

Optička svojstva tkiva utiču na interakciju tkiva sa laserskim zracima specifičnih talasnih dužina. U slučaju tkiva parodoncijuma, optička svojstva zavise od stepena pigmentacije, sadržaja vode, mineralnog sastava, toplotnog kapaciteta, koji se odnosi i na toplotnu provodljivost i gustinu tkiva, i posledica transformacije toplote (denaturacija proteina, vaporizacija vode, topljenje minerala). Kako se zna da je kost klasično kompozitno tkivo koje u svom sastavu ima 67% neorganskih minerala (kalcijum-hidroksiapatita) i 33% kolagena i nekolagenih proteina, dok je gingiva izgrađena od fibroznog tkiva različitih gustina povezanih međusobno komponentama vanćelijskog matriksa uz veliki procenat vode (70%), njihova optička svojstva su određena navedenim specifičnim sastavom. Dodatno, gingiva može biti hiperpigmentisana u slučaju velikog nakupljanja melanina u podsluzokožnom sloju. Ostali faktori koji određuju interakciju lasera i tkiva uključuju procese provođenja toplote i rasipanja, stepen prokrvljenosti i mogućeg zapaljenja tkiva, kao i sposobnosti progenitornih ćelija da učestvuju u regeneraciji tkiva. Svaka talasna dužina energije lasera apsorbovana je u većem ili manjem obimu u komponentama oralnih tkiva, kao što su voda, pigmenti ili hidroksiapatit [27].

Znajući da CO_2 laser (10600 nm talasne dužine) ima visok koeficijent apsorpcije u vodi, pogodan je za primenu u mekotkivnoj hirurgiji, dok nema dovoljno kvalitetnih podataka u literaturi o opravdanoj kliničkoj primeni na čvrstim tkivima usne duplje. Zrak lasera Nd:YAG (1064 nm talasne dužine) i diodnih lasera (talasne dužine od 800 do 950 nm) ima manji koeficijent apsorpcije u vodi u odnosu na CO_2 lasere, a značajno su apsorbovani u pigmentnim tkivima, dok su laseri Er,Cr:YSGG i Er:YAG (2780 i 2940 nm talasnih dužina) visoko apsorbovani i u vodi i hidroksiapatitu [28]. Stoga bi trebalo da kliničari za svaki klinički slučaj zasebno utvrde specifične ciljeve lečenja i zatim odaberu odgovarajuću tehnologiju (laser ili neku drugu) kako bi se postigli najbolji rezultati.

Za mnoge intraoralne mekotkivne hirurške procedure laser je adekvatna zamena skalpelu. CO_2, Nd:YAG i diodni laseri se najčešće koriste za mekotkivne procedure kao što su frenektomija, gingivektomija i gingivoplastika, epitelizacija periodontalnog režnja, uklanjanje granulacionog tkiva, oslobađanje dentalnih imlantata, ablacija, incizione i ekscizione biopsije benignih i malignih tumora, zračenje aftoznih ulceracija, koagulacija donorskog mesta slobodnog gingivalnog grafta i gingivalna depigmentacija. Pored toga, dokazi bržeg zarastanja mekih tkiva zavisni su od talasne dužine lasera i veoma osetljivi na gustinu energije. Većina studija koje istražuju zarastanje u ispitivanju koriste talasne dužine CO_2, Nd:YAG i diodnih lasera. Poređenjem zarastanja tkiva između Nd:YAG i CO_2 lasera pokazano je da CO_2 laser primenjen na oralnoj, orofaringealnoj i laringealnoj mukozi dovodi do značajno bržeg zarastanja u odnosu na laser Nd:YAG, ali je u oba slučaja zarastanje sporije u odnosu na rane nastale skalpelom [25]. Zarastanje je bilo podjednako za skalpel i laser Nd: YAG kada je upotrebljena niža snaga lasera od 1,75 W i 20 Hz. Dodatno, histološka istraživanja pokazala su da laseri velike snage (snaga u vatima), dugog pulsa, velikog broja ponavljanja (herci) i dugog vremena interakcije (dužina intervencije) povećavaju rizik od neželjenih efekata. Poređenje hirurških procedura laserom i skalpelom je široko istraženo u brojnim medicinskim i veterinarskim časopisima. Sa aspekta talasne dužine i različitih tkivnih parametara kao što su vreme incizije, krvarenje, otok, bol, i uopšteno zarastanje tkiva, objavljen je veliki broj različitih podataka, ali je u većini radova tehnologija lasera pokazala brojne prednosti, kao što su visok nivo kontrole radnog polja, efikasnost sprovođenja procedure, fleksibilnost nastavka i dodatnih opcija rada [27, 28].

Dejstvo lasera na zarastanje koštanog tkiva

Interakcija lasera i bioloških tkiva zavisna je od talasne dužine i posledičnog fototermalnog efekta, usled čega je većina efekata lasera velike snage na koštano tkivo potencijalno štetna. Čini se da su samo talasne dužine lasera Er:YAG i Er,Cr:YSGG pogodne za rad u kosti. Rezultati povećanja temperature na površini kosti izloženoj istoj ukupnoj energiji lasera pokazuju rang $1,4–2,1^0$C za CO_2 laser, dok za laser Nd:YAG iznose $8,0–11,1^0$C [29, 30]. Ovi rezultati ukazuju da je za ablaciju potreban relativno tanak sloj mekog tkiva poduprt okolnom kosti (bukalna, gingivalna i alveolarna mukoza). Ukoliko se koristi laser Nd:YAG relativno niske gustine energije, treba emitovati zrak u kratkim intervalima kako bi se sprečilo oštećenje kosti. Utvrđeno je da ukoliko se koristi laser Er:YAG u pulsnom modu pri energiji od 100 mJ/puls i 10 Hz, dobijaju se dobro definisani intrakoštani isečci bez tragova topljenja ili karbonizacije [29–32]. Slika 9 pokazuje da je grupa tretirana laserom izazvala brže formiranje kosti u odnosu na kontrolu [33].

Tehnika infracrvene spektroskopije sa Furijeovom transformacijom, razlučujuća/disperzivna energetska rendgenska spektrometrija i rendgenska difrakciona analiza pokazale su adekvatan odnos kolagena i hidroksiapatita u tankom sloju, koji se karakteriše blagim povećanjem u odnosu kalcijumi/fosfati ozračene površine usled stvaranja tetrakalcijum-fosfata, pokazujući da je hemijska struktura kosti slična onoj posle rada u kosti borerom, dok osteotomije CO_2 laserom dovode do izrazite karbonizacije, topljenja mineralne faze i odloženog zarastanja [29]. Takođe, nedavne studije govore u prilog talasnoj dužini Er,Cr:YSGG kao veoma pogodnoj za rad u kosti, jer energetskom rendgenskom spektrometrijom nije zabeležena promena u odnosu kalcijuma/fosfata, niti su nađeni znakovi karbonizacije ili topljenja. Promene površina cementa i dentina ispitivane su posle primene različitih talasnih dužina lasera CO_2, Nd:YAG i Er:YAG. Pokazano je da navedeni laseri mogu uspešno biti korišćeni za uklanjanje čvrstih naslaga ukoliko se odabere talasna dužina sa minimalnom apsorpcijom od strane mineralnih tkiva. Ovo je važno sa aspekta termalnog oštećenja pulpnog tkiva i neželjenog uklanjanja čvrstih struktura korena zuba. Mineralna faza cementa i dentina, karbonatni hidroksiapatit, ima intenzivnu apsorpciju zraka iz srednjeg infracrvenog spektra [27–32].

Posledično, od svih ispitivanih talasnih dužina, laser Er:YAG bi bio instrument izbora za efikasno uklanjanje tvrdih zubnih naslaga, nagrizanje mineralnog tkiva kosti i stvaranja biokompatibilne površine za ponovni pripoj ćelija i tkiva. Suprotno, ukoliko bi se upotrebio CO_2 laser, čak i pri niskoj energiji, analiza infracrvenom spektroskopijom sa Furijeovom transformacijom pokazuje prisustvo toksičnih hemijskih ostataka cijanamida i cijanata, praćenih nedosatkom pripoja režnja na tretiranoj površini zuba. Stoga CO_2 laseri imaju ograničenu primenu u subgingivalnoj parodontalnoj terapiji. Pri energijama od 100 do 400 J/cm^2 za CO_2 i 286 do 1,857 J/cm^2 za laser Nd:YAG opisan je određen stepen morfoloških promena na površini korena nastalih dejstvom lasera, kao što su efekat kavitacije, topljenje i remineralizovanje globula, promene u strukturi proteina korena, površinskih pukotina, i stvaranje površinskog sloja, što je direktno bilo zavisno od gustine primenjene energije. Suprotno u odnosu na navedene rezultate, kada je primenjen laser Nd:YAG, pri manjim gustinama energije ili kombinaciji niže gustine energije uz defokusiran zrak, pokazano je da je pogodan za uklanjanje razmaznog sloja na površini korena bez izazivanja posledica po tkivo cementa i/ili dentina, ili povećanja temperature do nivoa koji bi uzrokovao ireverzibilno oštećenje pulpe [34, 35, 36].

Relativno nov laser, Nd:YAP sa talasnom dužinom 1340 nm, ispitivan na površini izvađenih zuba, pokazuje prisustvo promena na tkivu uzrokovanih toplotom pri gustinama primenjenih energija od 509 do 1274 J/cm^2. Stepen oštećenja je direktno povezan sa povećanjem gustine energije i progresivno raste od nastajanja pukotina na površini cementa do razvoja dubokih pukotina, topljenja i duboke ablacije cementa uz izlaganje dentina ispod.

Nedavno su laser Er,Cr:YSGG i u manjem obimu laser Er:YAG promovisani za primenu u produženju kliničke krune bez podizanja gingivalnog režnja, iz estetskih i protetskih razloga. Očigledno, estetsko produženje krune može se jednostavno izvesti laserima ukoliko su klinički kratke krune rezultat izražene gingive ili nedostatka pasivne erupcije zuba. U takvim slučajevima povećanje dubine gingivalnog sulkusa se javlja usled izraženog volumena mekih tkiva [34–37].

Primena lasera u lečenju hronične parodontopatije zasniva se na regeneraciji mekotkivnog pripoja, cementa, periodontalnog ligamenta i okolne alveolarne kosti, uz značajno smanjenje broja subgingivalnih patogenih bakterija. Ograničen je broj istraživanja koja govore u prilog efikasnijem laserskom uklanjanju subgingivalnih bakterija u odnosu na standardno lečenje. Većina studija koja ispituje baktericidni efekat opisuje dozno zavisnu vezu. Međutim, u mnogim studijama gustina energije često nije navedena ili ne može biti izračunata usled nekompletnog spiska parametara. Konačno, ugao zračenja može varirati od 0 do 90^0, čime je izračunavanje gustine energije gotovo nemoguće [38–41].

Jedna od prvih *in vivo* studija koja je opisala smanjenje broja patogenih bakterija posle zračenja laserom Nd:YAG pokazuje smanjenje bakterija *Porphyromonas gingivalis*, *Prevotella intermedia* i *Actinobacillus actinomycetemcomitans* [38]. Međutim, na zubima izvađenim sedam dana posle + tretmana nađena je rekolonizacija površina korena ozračenih laserom mnogobrojnim bakterijama. *In vitro* studije primenom lasera Nd:YAG uz niže primenjene energije opisale su ablaciju čvrstih naslaga bez neželjenih efekata po dentin ili cement. Takođe je nađena linearna veza između nivoa energije, broja mikroorganizama i koncentracije hemoglobina i minimalne energije potrebne za baktericidni efekat, odnosa prijemčivosti mikroba za energiju lasera i oštećenja čvrstih zubnih naslaga, cementa, dentina, čak i na pojedinačnom uzorku. Takođe, pokazana je raznolikost u boji, debljini, sastavu, teksturi i sadržaju vode [38–41]. Diodni laser (805 nm), primenjen uz standardnu kauzalnu terapiju parodontopatije, doprinosi smanjenju subgingivalnih bakterija u parodontalnom džepu dubine 4 mm. Međutim, mnoge *in vivo* studije opisale su zastupljenost vijabilnih bakterija posle subgingivalnog zračenja laserom [38, 40, 41].

ZAKLJUČCI

U ovom radu opisano je zračenje bioloških tkiva specifičnim talasnim dužinama lasera. U pregledu literature su proučene interakcija zubnih tkiva i različitih tipova lasera, energija i talasne dužine, a prikazani rezultati mogu poslužiti za odabir adekvatnijih parametara za primenu lasera, bez izazivanja destrukcije tretiranih mekih i tvrdih zubnih tkiva. Pored specifične primene lasera, u ovom radu su opisane i osnove stimulisane emisije, principi rada lasera, glavni tipovi instrumentacije lasera, prednosti i nedostaci primene određenih vrsta lasera, kao osnova za bolje razumevanje veoma zahtevnih oblasti primene lasera u dentalnoj medicini.