Laser physics and laser-tissue interaction

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Summary

Introduction

In this chapter we intend to describe the nature of laser light and its interactions with biological tissues. Our aim is to place physics inside a "black box" laser sale apparatus for non-specialist professionals; and to make the mechanism responsible for the effects observed after laser irradiation clear. Bearing the objectives in mind, we will make use of many graphical resources as well as common sense examples to aid the reader's understanding of this issue. Associations with common sense examples must be handled carefully because they are only analogies that will be used to describe the abstract concepts of physics and the interaction mechanism of laser with matter. For a more specialized theory about laser physics the reader must look in to other books [1] [2] and search for laser-tissue interaction in [3] [4].

Table 1 lists the physical parameters and the constants used in this chapter. One example is the name given to the energy distribution on a certain area. This laser parameter has different names: energy density, radiant exposure, fluence, or dose. In this chapter we use the name that is recommended by the International Systems of Units [5]: radiant exposure, which is expressed in [J/m^2]. In the same way the parameter representing the power distribution on a certain area will be designated: irradiance, and will be expressed as [W/m^2].

Light Waves

Light emanating from sources, laser sources or not, is wavelike in nature. To visualize the wave characteristic of light is not an easy task for nonspecialists, but this concept will be clarified in this section.

Light can be described by a combination of time-varying propagation of electric $(\vec{E})$ and magnetic $(\vec{H})$ fields through space. These fields oscillate at a certain frequency (ν); i. e., the field value increases and decreases ν times in one second. The frequency at which these fields oscillate and their wavelength (λ) are related by: $\lambda\nu = c/n$, where c is the speed of light in a medium with refractive index n.

To visualize the electric and magnetic (electromagnetic) field we can compare the action of this field with the gravitational field. For example, a ball which falls down on the earth surface is in fact attracted by the earth, because the earth is "a bigger ball" with a larger mass than the ball, and both are attracted together. Another mechanic example is a mass coupled with a spring: if our ball is coupled with a vertical spring suspended in the air, the ball does not fall to the earth surface; the spring restores the movement back up and the ball oscillates vertically to dissipate all the energy heating the environment. The electromagnetic filed acts likewise on the charges of

atoms and molecules: when a positive (or negative) charge is placed under an electromagnetic field, it will be displaced from its position; when the field oscillates with frequency ν, the charge will also oscillate at the same frequency.

As we know, our body is fulfilled with charges. When an electromagnetic field interacts with our tissues, the molecules will oscillate at the same frequency of the wave. This will heat our body, trigger chemical reactions, or lead to other mechanisms. In Figure 1 we can visualize the explanation for the electromagnetic field in the space (Figure 1-a); and in time (Figure 1-b).

When a charge is submitted to the influence of a wave its movement can also be described by the electromagnetic wave observe Figure 1-c and consider a positive charge at the origin; when the electric field vector of a wave, described by the arrow, interacts with the charge, its movement will follow the amplitude of the electric field. Figure 1-c shows the electric field at a certain angle; if all photons have their electric field running in the same direction, the beam is named polarized beam; if the photons oscillate at a nonspecific direction, the beam is nonpolarized as represented in Figure 1-d.

The different frequency of the electromagnetic field will determine the energy of the wave (photon). The frequency range of different photons can be visualized in the upper scale in Figure 2; the second scales correspond to the energy, and the third to the wavelength. The correlation of the energy (E) of a photon with its frequency (ν) and wavelength (λ) is giving by the following equation:

$$E = h\nu = \frac{hc}{\lambda};$$

where h is the Planck constant (6.625×10^{-34}Js) and c is the speed of light. A more useful equation is:

$$E = \frac{1.24}{\lambda};$$

where E is given in eV and λ in μm.

In the same Figure 2, the most interesting spectral region for laser application is expanded and compared with the water absorption spectra (adapted from [6]). The absorption coefficient is expressed in cm^{-1}, the wavelength of the photons can be visualized in the lower scale and is given in micrometers (μm), and the upper scale gives the photon energy in eV.

Laser physics

Laser design

Some basic conditions must be satisfied so that a functional laser system can be obtained. First of all there must be a material named active medium, that allows population inversion. It is unlikely that this inversion occurs in nature but it can occur in some materials. The most probable behavior for electrons is to remain at the ground energy level, whereas in an active medium excited electrons are located at a higher energy level for a longer period of time, allowing the stimulated emission. This phenomenon will described in the following paragraphs.

In Figure 4 it is possible to visualize the description of the main instruments for a laser system. The active medium will be excited by means of a pumping source, which can be another laser, an electric current or a nonlaser source. When population inversion occurs, stimulated emission will take place and an avalanche of photons will emitted. These photons can resonate between the two mirrors; the output mirror is a partially reflected mirror, thus allowing photon emission.

Stimulated emission

In nature all systems tend to reach the lower energy state. A typical example is a rock on a hill; the rock tends to roll down to reach the valley, river, or the sea. Electrons act in the same way, occupying states with lower energy. Which is represented in Figure 5-a; If the lower state is totally occupied, the second lower state will start being occupied. But when the system has more energy, like thermal energy, the electron can acquire this energy and transit to upper states.

The origin of stimulated emission can be visualized Figure 3 by four boxes. Figure 3-a represents the nonexcited atom with its electron in the ground state. Stimulated absorption of one photon will excite the atom and the electron will transit to an upper energy state (Figure 3-b). When a spontaneous emission occurs (Figure 3-c) a photon will be emitted and will stimulate the emission of another photon (Figure 3-d).

For the stimulated emission to occur, it is necessary that the active medium presents population inversion. This situation is described by the energy-state-transition diagram of Figure 5-c: the most populated state is not the ground sate, but an upper state, named long-lived excited stated. With all the electrons in this upper state, stimulated emission can occur more efficiently, thus producing the laser beam.

Monochromaticity

The monochromaticity of laser light originates from the different energies during the stimulated emission described in Figure 3. When a photon is emitted spontaneously, its energy is well-defined and the other photons stimulated by the first one have the same energy. As a consequence, the laser beam output is composed of well-established photon energy; i. e., a specific wavelength. If the source does not emit photons with the same energy, the emission spectra will be broad as in the case of a LED (Light Emitting Diode) or the sun in Figure 7.

Directionality

Laser emission occurs only in the direction toward which the system resonates; i. e., in the longitudinal axis connecting by the first mirror to the two lateral faces of the laser medium and the second mirror (Figure 6). Otherwise, photon emission can occur randomly at any direction in a lamp bulb, spreading out the energy: consequently leading to a much lower irradiance than that of a laser beam.

Coherence

Laser light has spatial and temporal coherence. This coherence means that all the photon waves that compose a laser pulse are correlated in space and time. As described before, all the photons oscillate at the same frequency (monochromaticity), and beyond this frequency oscillation of the laser photons starts at the same time. In other words, when the amplitude of the electric field of one photon (Figure 1-b) is at its highest value, all photons have amplitude at this highest value too, which means temporal coherence.

Consider that in a certain position the amplitude of the electric field has a particular value. Spatial coherence means that at a certain time, all the other wave photons will have the same amplitude value at λ meters away from the first photon, and the next surrounding wave photons will also have the same amplitude value. Therefore, all photons will be correlated with the first photon.

The origin of spatial and temporal coherence in a laser beam is described in Figure 8 and a common sense analogy to explain the coherence is presented in Figure 9.

Laser systems in life science

The main laser wavelengths applied in life science are listed in Table 2. The Excimer lasers, nitrogen, and higher harmonic of neodymium lasers emiting at the ultraviolet spectral region with the highest photon energy. The main interaction mechanism for these lasers is photoablation. There are laser systems with emission wavelengths in the visible spectral region

and their main interaction mechanism can be described as photochemical. Finally, the laser systems with emission in the infrared spectral region exhibit an interaction mechanism dominated by thermal action.

The photon energy changes with its wavelength. For longer wavelengths, as in the case of lasers emitting in the infrared spectral region, the photon energy is lower than the energy of a photon in the visible spectral region. Likewise, the energy of the latter photon is lower than that of a photon emitting in the ultraviolet spectral region. The energy of photons in laser systems (Table 2) can be compared with the main interatomic bond energies encountered in biological molecules (Table 3).

Laser beam output

In a laser system (continuous or pulsed) it is necessary to describe the density of photons in space and time. In other words, it has to be said how many photons are present in a determined volume or instant of time. To facilitate calculation and explanation, we will use the area of a irradiated surface instead its volume; i. e., the density of photons in a determined area instead of the number of photons in a determined volume.

Spatial profile

The most common spatial profile of a laser beam in clinical practice is the multimode or the Gaussian beam profile. The transversal profile of that kind of laser beam can be visualized in Figure 10. Figure 10-a represents a laser cavity with the traced line indicating a transversal point of view. Figure 10-b represents the transversal irradiance, if the laser is continuous; or transversal radiant exposure, if the laser is pulsed. For a symmetric beam, the same distribution can be described by Figure 10-c. The beam radius is defined at the position where the irradiance, or radiant exposure, falls down to e^{-2} (14% of the maximum value).

Now, for a constant power or energy per pulse the transversal area can change (Figure 12). The lower divergence of a laser source can change the transversal area a little, but it can be considered approximately equal the original area near the laser cavity. But if the beam passes through a lens or a fiber, the transversal area changes drastically as shown in Figure 12-d.

Consider a continuous laser with a diameter of 1mm emitting an average power of 1W. For a laser-tissue interaction, a useful parameter is not only the power but also the irradiance, also named power density. To calculate the irradiance of a beam we should divide the power by the beam transversal area:

$$I = \frac{P}{A} = \frac{1W}{\pi\,(0.5\text{mm})^2} = 1.3\frac{W}{mm^2} = 130\frac{W}{cm^2};$$

$$I = 130W/cm^2$$

Temporal profile

The last paragraph discussed the distribution of photons in space; Figure 11 will now represent the distribution in the time of a pulsed laser and Figure 13 will show three different temporal profiles of laser beams. Figure 11 represents three pulses emitted during one second with 50mJ in each pulse and a pulse width of 50ms. The pulse width represents how long the laser system emits the 50mJ energy.

As presented in Figure 11, these pulses occur 3 times per second and the laser emits at a frequency of 3Hz. Taking these together with the energy per pulse (50mJ) and the time width of each pulse (50ms), it is possible to calculate the peak power (P_p) and the average power (P_a) of this laser beam.

The peak power will be determined as follows:

$$P_p = \frac{E}{\Delta t} = \frac{50mJ}{50ms} = \frac{0.05}{0.05}\frac{J}{s} = 1\frac{J}{s};$$

$$P_p = 1W.$$

If the laser is turned on only 3 times in one second and each time corresponds to 0.05s (50ms), the total time during which the laser is "turned on" is 0.15s; consequently for the same period of one second the laser is "turned off" for 0.85s. To obtain the average power we have two possibilities. The first is:

$$P_a = \frac{P_{on}(\Delta t_{on}) + P_{of}(\Delta t_{of})}{total\ \ time} = \frac{1W(0.15s) + 0W(0.85s)}{1\,s} = 0.15 + 0;$$

$$P_a = 0.15W.$$

A second and easier possibility is:

$$P_a = Ef = (50mJ)(3Hz) = (0.05)(3)\frac{J}{s} = 0.15W;$$

$$P_a = 0.15W.$$

This example is valid for a pulsed laser with a variable pulse width. Now, if our laser is a chopped laser, the average power is easier to calculate. In a chopped laser, the beam is interrupted in such a way that it produces power profile as described in Figure 13-b. For this emission profile, the laser is "turned on" for some time and "turned off" for the same period of time; this alternation between on and off is repeated at a frequency (f) chosen by the operator. Independent of the selected frequency, the average power will always be half of the peak power:

$$P_a = \frac{P_p}{2} = \frac{1W}{2} = 0.5W.$$

In clinical practice it is important to know that an irradiation of 1W at a chopped mode (interrupted) the average power reaching the tissue is only 0.5W.

Laser-tissue interaction

Optical behavior in a tissue sample

Biological tissues have an average refractive index higher than that of air. When light interacts with the tissue surface, part of the light is reflected at the air/tissue interface; while the remaining light interacts with the tissue and penetrates into. Figure 14 shows the behavior of a laser beam interacting with the structure of absorbers and scatters on a tissue slab. The arrows indicate photon propagation: reflection at the air/tissue interface; backscattered photons, also named diffuse reflection; and absorbed and transmitted photons, also named diffuse transmission.

The photon density into the tissue is approximately described by the following equation:

$$I(z) = I_0 e^{-\alpha z};$$

where α is the attenuation coefficient and z the axial distance into the tissue, measured from the surface (see Figure 14). The attenuation coefficient measures how fast the photon density decreases into the tissue; this value depends on the tissue characteristics and on the density of absorbers and scatters in the tissue.

Consider the example of a tissue with an attenuation coefficient of $2cm^{-1}$. The irradiance into the tissue will be:

$$I_2(z) = I_0 e^{-2z}.$$

Now, the irradiance at 0.5 cm^{-1} into the distance will be:

$$I_2(z) = I_0 e^{-2(0.5)} = I_0(0.37);$$

i. e., half centimeter beneath the surface, the irradiance is only 37% of the initial value. In other words, if at the surface the irradiance was $1W/cm^2$, half centimeter beneath the surface it will be $0.37W/cm^2$.

The attenuation coefficient changes for different wavelength and tissues. The water is the main compound in soft and hard tissue and will determine the attenuation. According to the water spectrum (Figure 2-D) and ignoring some scattering by the water itself, it is possible to determine how deep the wavelength travels into the water, taking the absorption coefficient for different wavelengths.

Interaction mechanisms

The consequence of the interaction of a laser beam or nonlaser source with a target tissue will be determined by the beam irradiance, interaction time, and absorption coefficient of the tissue. Figure 15 describes the mechanism that predominates in laser-tissue interaction approximately (adapted from [7]). The diagonal line represents the radiant exposure. It is easy to see that two different irradiances combined with two different interaction times can produce the same radiant exposure. In the following sections we will discuss the main interaction mechanism taking place during laser irradiation in medical practice: photochemical and photothermal interactions. The nonlinear mechanisms will not be described in this chapter.

Photochemical interaction

Approximately, chemical reactions involving photons can be classified as phtotochemical reactions. The most popular example is photosynthesis; in our body other examples are the production of melanin and of the light-induced compound Vitamin D. All these reactions involve photons. The main idea of the photochemical treatment is to use a chromophore receptor acting as a catalyst; and a general reaction for the photochemical interaction is expressed in the sequence:

$$A + h\nu \Leftrightarrow A^*$$

The reagent can be a molecule or a radical; the absorption of a photon with energy $h\nu$ produces the excited state A*. The inverse reaction can also occur with the desexcitation of A* and the emission of a photon.

Photothermal interaction

The photothermal interaction is characterized by reactions that occur after a local temperature increase. In this mechanism different effects are included: coagulation, vaporization, carbonization, melting, among other effects.

These effects can be achieved by different wavelengths, emission modes, and pulse profiles. Heat production by light absorption and consequent conduction to the surrounding tissue can be visualized in Figure 17 for different time delays at the surface. In this figure, it is necessary to consider that the tissue irradiation occurs at $t = 0$ and the pulse width is much shorter than 0.5ms.

Spatial distribution into a tissue block can be visualized in Figure 18. The solid lines represent isotherms; i. e., regions where the temperature shows the same value. An example is when the tissue between the pulse and the first solid line increases T_1 ºC, while the tissue between the first and the second line increases T_2 ºC.

During tissue irradiation with a laser beam, the tissue can be removed through ablation mechanism or vaporization. This removal laser is represented as the first layer in Figure 16. However, photons penetrate further into the tissue and will be absorbed by it. The light will penetrate into the tissue and there will be a distance where the intensity falls to 37% (1/e) of the initial intensity. The distance between the surface and this depth is defined as the optical penetration depth (z_{optic}); this depth is represented by the second layer in Figure 16.

In addition, the photons absorbed in the second layer will heat this layer and dissipate to surrounding regions where the temperature is lower. Thermal dissipation will also occur into the tissue. The depth where the temperature decreases to 1/e of its peak value will be the thermal penetration depth $(z_{thermal})$, described as:

$$z(t)_{thermal} = (4\kappa t)^{-1}$$

where κ is the temperature conductivity of the tissue and t is the time of laser action on the tissue (laser pulse duration). The temperature conductivity is related with the heat conductivity (k) expressed in W/mK, the tissue density (ρ) expressed in kg/m^3, and specific the heat capacity (c) expressed in kJ/kgK

For several applications it is important to adjust the duration of the laser pulse; i. e., the time of the laser pulse action on the tissue, in order to minimize thermal damage to adjacent structures. By adjusting this laser pulse it is possible to minimize necrosis of the surrounding tissue [8]. This is obtained by equating the optical penetration depth (z_{optic}) to the thermal penetration depth $z_{thermal}$, hence: $z(t)_{optical} = (4\kappa t_{thermal})^{-1}$; and the interaction time (t) will be renamed as thermal relaxation time $(t_{thermal})$.

The importance of the thermal relaxation time will be explained by the following considerations: a) for a laser pulse duration $\tau < t_{thermal}$, heat does not even diffuse to the distance given by the optical penetration depth; b) for $\tau > t_{thermal}$, heat can diffuse to a higher value than the optical penetration depth and thermal damage of the adjacent tissue is possible.

Thermal effects on soft and hard tissues

The laser parameter together with the optical and thermal properties of the tissue will determine the spatial and temporal distribution of the temperature inside the tissue, and the maximum reached temperature and the time during which the tissue is submitted to the laser will lead to different biological effects. The biological effects on soft and hard tissues are summarized in Table 4; for specific details see references [3] [9].

Table 1 – Physical parameters and constants used in this chapter.

Parameter	Symbol	Unit
Energy	E	J
Power	P	W
Radiant exposure (Energy density)	R	J/m^2
Irradiance (Power density)	I	W/m^2
Time	t	s
Electric field	$\vec{E}$	V/m
Magnetic field	$\vec{H}$	A/m
Photon frequency	ν	Hz
Wavelength	λ	m
Speed of light in vacuum	$c=3x10^8$	m/s
Refractive index	n	-----
Planck constant	h=	
Absorption coefficient	α	cm^{-1}
Laser frequency	f	Hz

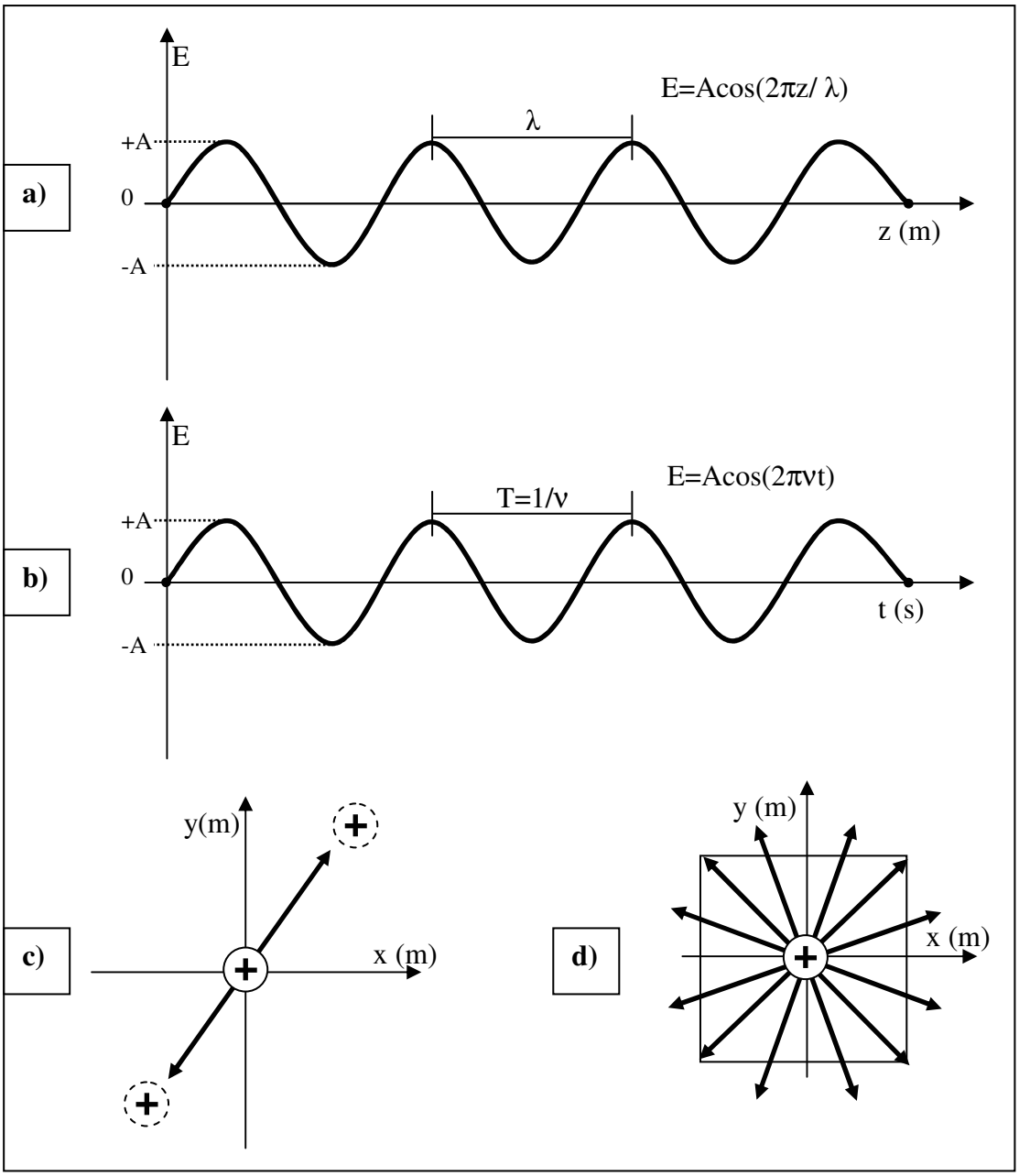

Figure 1 – a) The electromagnetic wave is a function of the distance at a certain time (t=0). The separation between two maxima of the wave amplitude is the wavelength λ. b) Amplitude of an electromagnetic wave as a function of time at a point in space (z=0). The period T is the time necessary for the wave to complete one cycle; i. e., starting from an amplitude +A, decreasing to –A and returning to the initial value +A. The inverse of the period is the frequency of the wave; i. e, number of cycles carried out in one second. c) Crossection of item (a) with representation of a positive charge displaced by the action of an electromagnetic field. If the wave oscillates in a determined direction, the electromagnetic field is named polarized, and the charge will be displaced in the same direction of the wave. Otherwise, if the wave is nonpolarized (item d), the wave can oscillate in any direction and therefore the charge will be displaced in any direction.

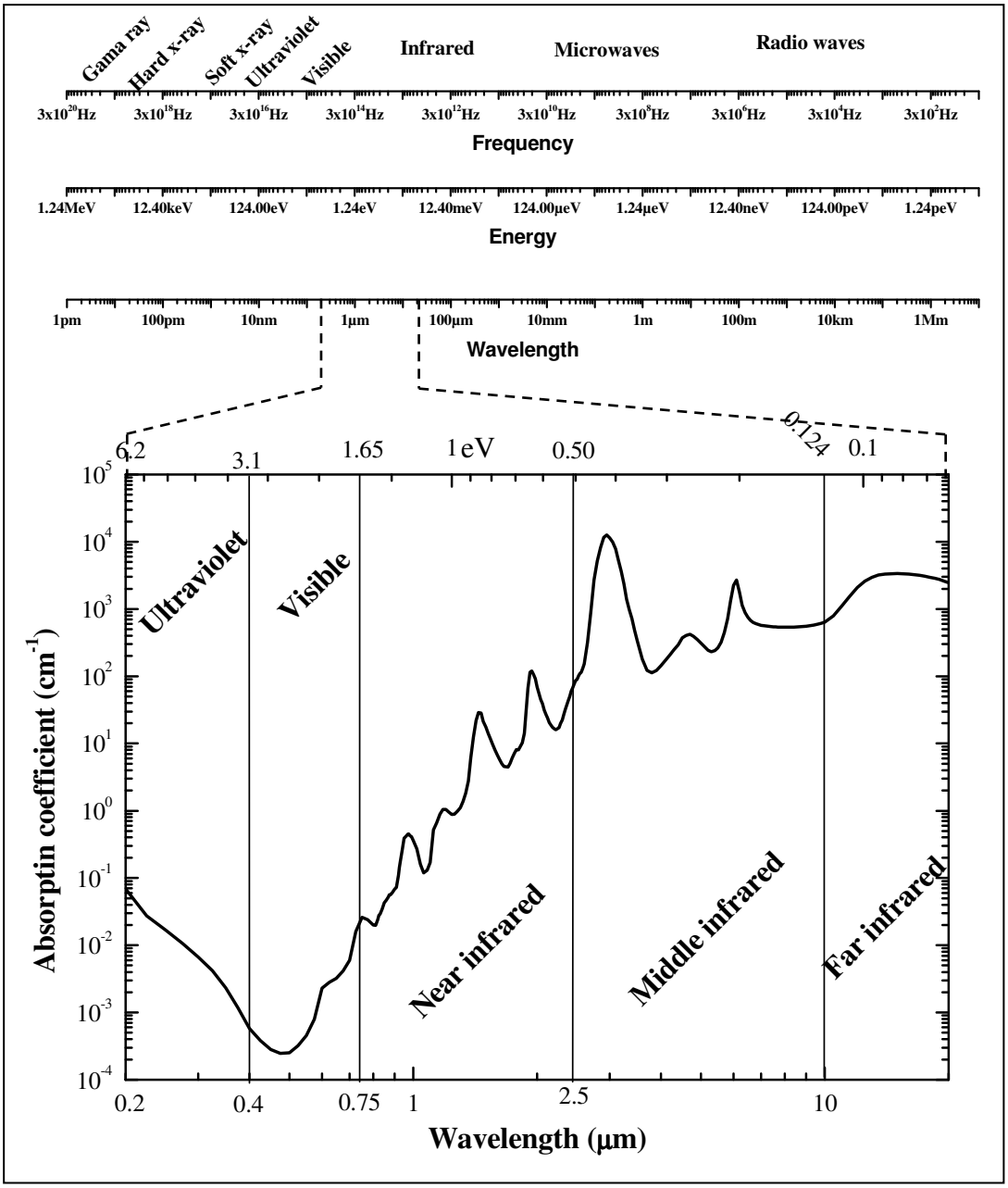

Figure 2 – Electromagnetic spectrum. The first upper scale represents the frequency of wave oscillation. The higher values represent the gamma ray and hard x-ray; when the frequency is decreased there are the soft x-ray, ultraviolet, visible, infrared, microwaves, and radio waves. The second scale represents the respective photon energy and the third gives the wavelength of the photon. The main interest in laser applications is the ultraviolet, visible, and infrared radiation; these three spectral regions are better visualized in the graphic and compared with the water absorption spectrum [6].

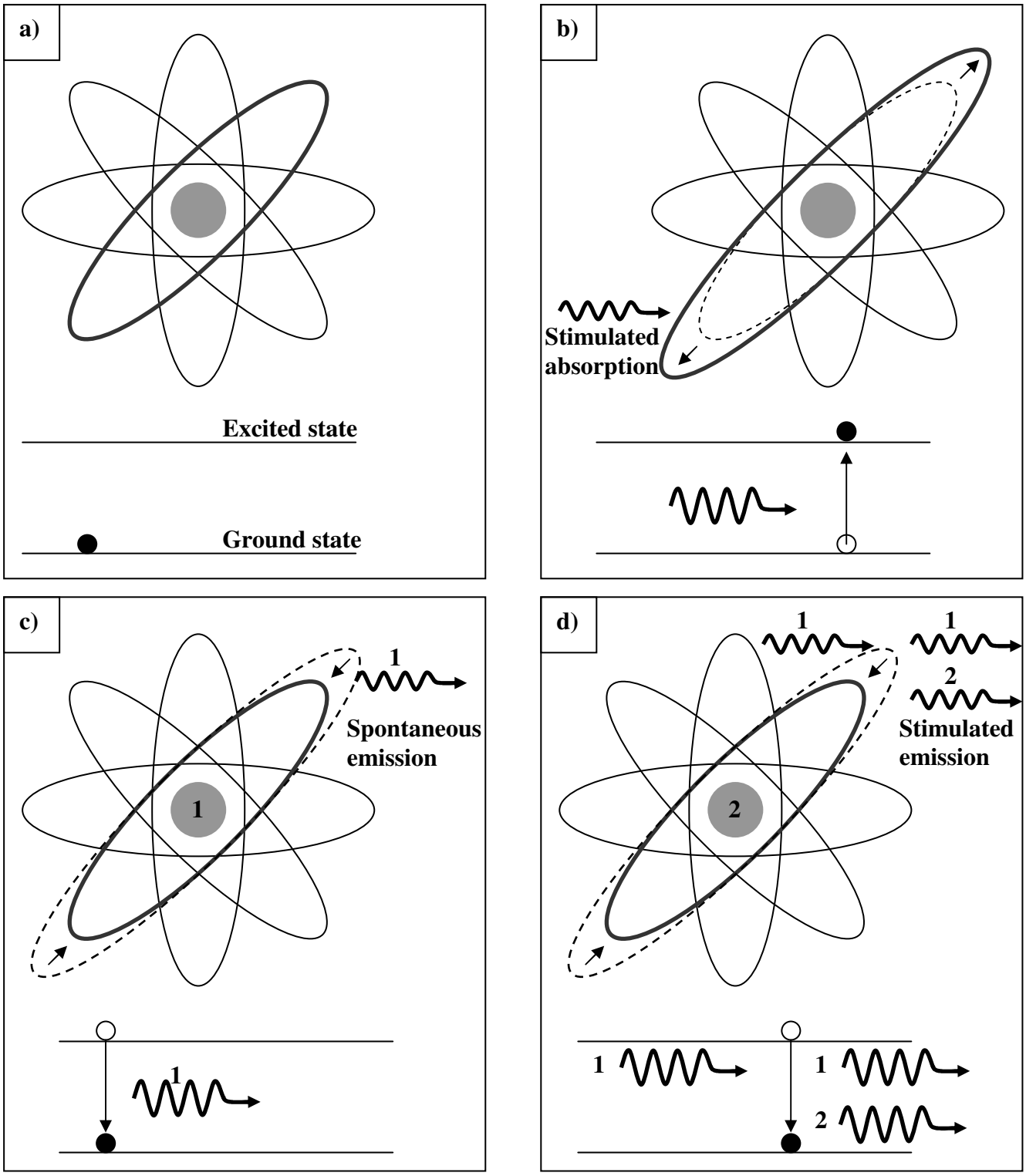

Figure 3 – The four boxes represent a sequence that originates stimulated emission. In each box there is described an atom with electrons in the ground state, and the horizontal lines represents the ground state and excited state of one electron. a) The first box represents the atom with the electrons in the ground state. b) In the second, a photon is absorbed and one electron goes to an excited state. c) The excited atom emits a photon spontaneously and the electron goes back to the ground state. d) The first spontaneously emitted photon induces the decay of a second excited energy state. Simultaneously, a second photon is emitted, having the same phase and wavelength as the first photon.

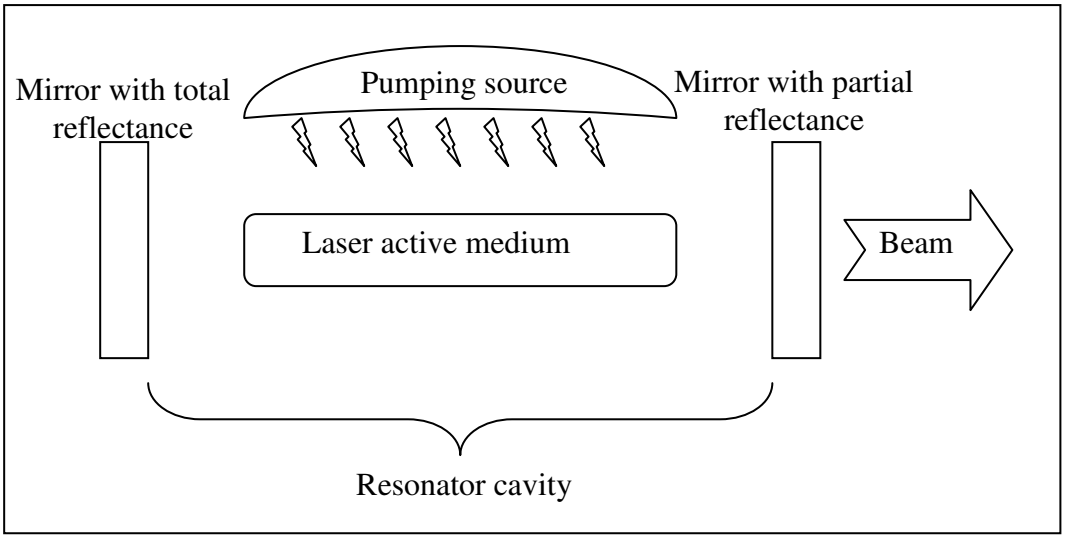

Figure 4 – Basic design for a laser system. The pumping source excites the electrons in the active medium and promotes population inversion and the consequent stimulated emission. The two mirrors act as an oscillator to amplify the stimulated emission in the longitudinal direction.

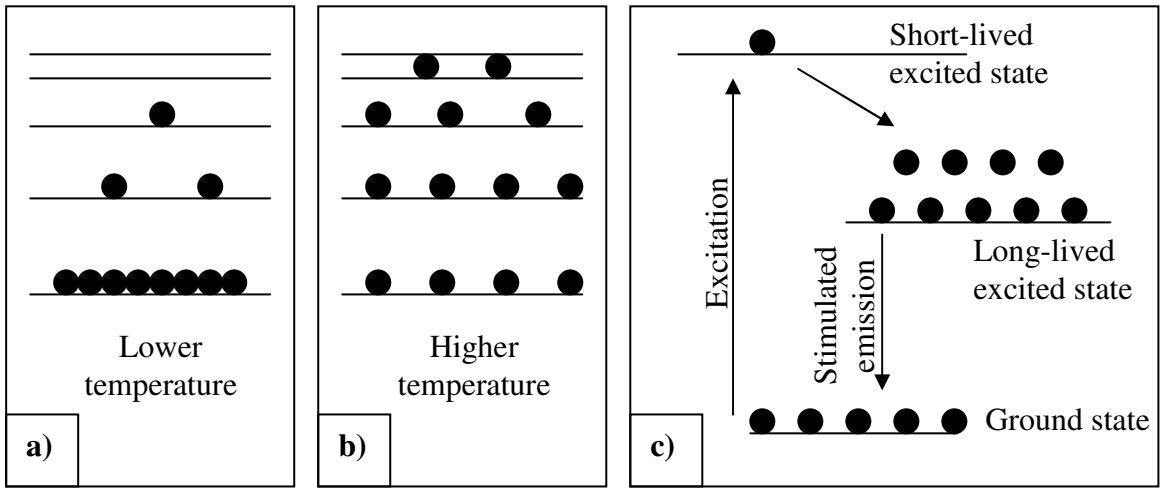

Figure 5 – Energy-state-transition diagrams of electrons at different temperatures: a) lower temperature, b) higher temperature, c) and a diagram representing the population inversion in a three-level laser system. Bu increasing the temperature it is possible to populate the upper energy levels, but it is not possible to reach a population higher than that of the ground level. Otherwise, for a laser active medium it is possible to increase the population of an upper state to values higher than the population of the ground state.

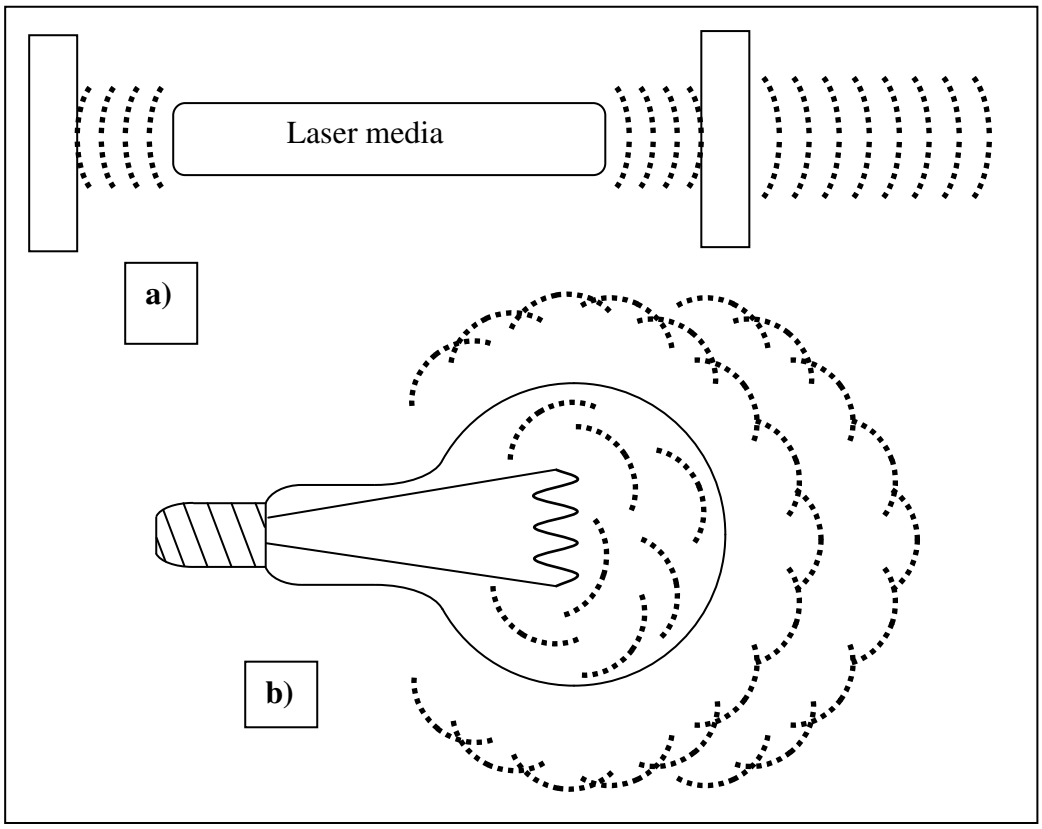

Figure 6 – Directionality: a) The upper figure represents a laser system that describes the directionality of the output beam. The laser emission occurs only in the direction that the system resonate; i. e., in the longitudinal axis connected by the first mirror to the two lateral faces of the laser medium and the second mirror. b) Otherwise, in a lamp bulb photon emission can occur randomly at any direction, spreading out the energy; as a consequence the irradiance (power density) is much lower than the irradiance of a laser system

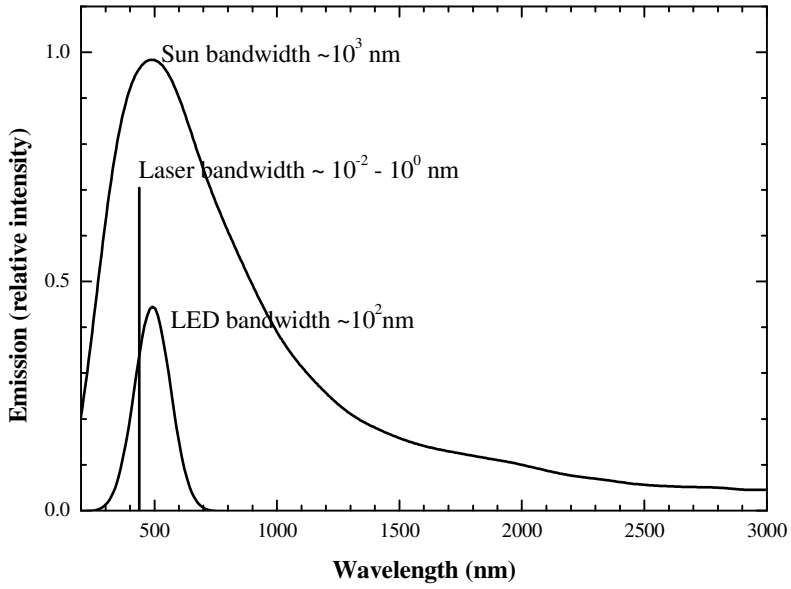

Figure 7 – Representation of the emission spectra of the sun, LED (Light Emitting Diode), and a laser system. The sun emission covers all the ultraviolet, visible, and infrared spectral range and the LED is a little narrow but still broad when compared with a laser emission. The bandwidth (a value that measure how large the source) of the sun is approximately 1000 nm, that of the LED is 100 nm, and the laser system shows bandwidths of approximately between 1 and 0.01 nm.

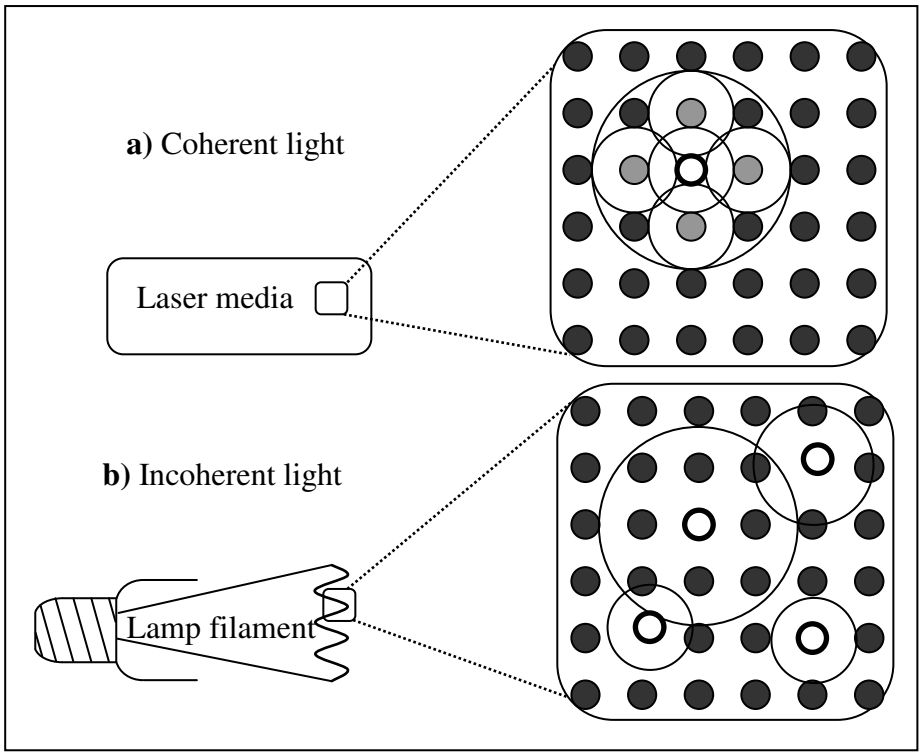

Figure 8 – Spatial and temporal coherence. a) In a laser active medium the spontaneous emission of one atom (represented by the hollow ball) stimulated the emission of the neighboring atoms (four gray circles). As a consequence, the photon wave of the first atom (big circumference) is at the same spatial position and time of the four photons emitted from the four neighboring atoms (four smaller circumferences). These five emitted photons are said to be in phase one with other. b) In a lamp filament, the electron current excites the atoms. Photon emission then occurs randomly at different time and position into the filament. The emitted light is composed of photon waves that are not correlated as in the case of a laser medium.

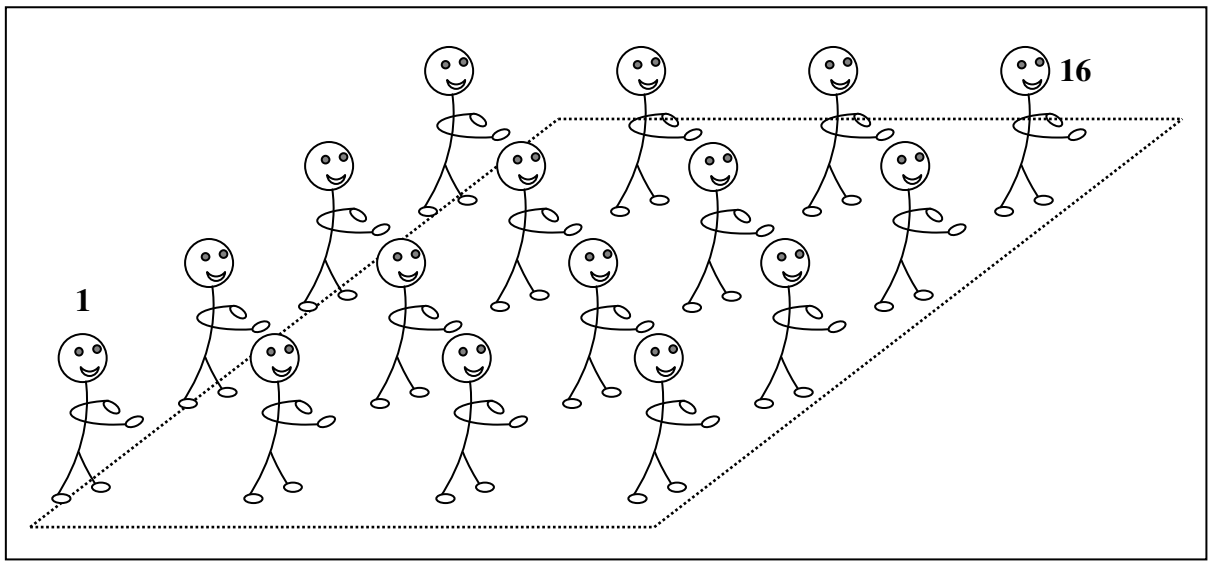

Figure 9 – Analogy to understand the spatial and temporal coherence of a laser beam. A military parade is a good example of peoples who have spatial and temporal coherence. In that kind of march, a first soldier, in the left position walks at the same frequency and relative spatial position as his neighbors. For this reason we can say that the soldier, number one, is in temporal and spatial phase with the other soldiers, including with the most distant soldier, number sixteen.

Table 2 – Laser systems for medical applications with their wavelengths and photon energy.

Laser systems	Wavelengths (nm)	Photon energy (eV)
Excimer - F_2	157	7.9
Excimer - ArF	193	6.4
Excimer - KrCl	222	5.6
Excimer - KrF	248	5.0
Excimer - XeCl	308	4.0
Nitrogen	337	3.7
Excimer - XeF	351	3.5
Double ionized argon	351/363	3.5/3.4
Argon	488/514.5	2.5/2.4
Metal-Vapour-Copper	510/578	2.4/2.1
Metal-Vapour-Gold	312/628	4.0/2.0
Krypton	530.9/568.2	2.3/2.1
Helium-Neon	543/594/604/612/632.8	2.28/2.09/2.05/2.03/1.96
Helium-Neon	1152/3391	1.08/0.37
Ruby	694	1.79
Alexandrite	720-800	1.72-1.55
Dye	400-900	3.1-1.38
Diode	600-1000	2.07-1.24
Ti:sapphire	700-1000	1.77-1.24
Neodymium (Nd:YAG)	1064/532/355/266	1.16/2.33/3.49/4.66
Neodymium (Nd:YLF)	1053	1.18
Holmium - Ho:YLF	2060	0.602
Holmium - Ho:YAG	2120	0.584
Erbium - Ct:Tm:Er:YAG	2640	0.470
Erbium - Er:YSGG	2780	0.446
Erbium - Cr:Er:YSGG	2790	0.444
Erbium - Er:YLF	2800	0.443
Erbium - Er:YAG	2940	0.422
Carbon dioxide	9000-11000	0.138-0.113
Free electron laser	800-6000	1.55-0.207

Table 3 – The main interatomic bond energies present in biological molecules. The bond energy can be broken by the direct absorption of a photon; this process is named photoablation and is accomplished mainly by lasers with emission in the ultraviolet region; wavelengths with photon energy higher than the bond energy.

Chemical bond	Energy (eV)
H bond	0.19
N – N	1.62
O – O	2.18
N – O	2.18
C – S	2.70
C – N	3.06
C – C	3.62
C – O	3.62
H – N	4.06
H – C	4.31
N = N	4.31
H – H	4.49
H – O	4.81
N = O	5.00
O = O	5.12
C = N	6.37
C = C	6.37
C = O	7.68
C ≡ C	8.68
C ≡ N	9.24
N ≡ N	9.80

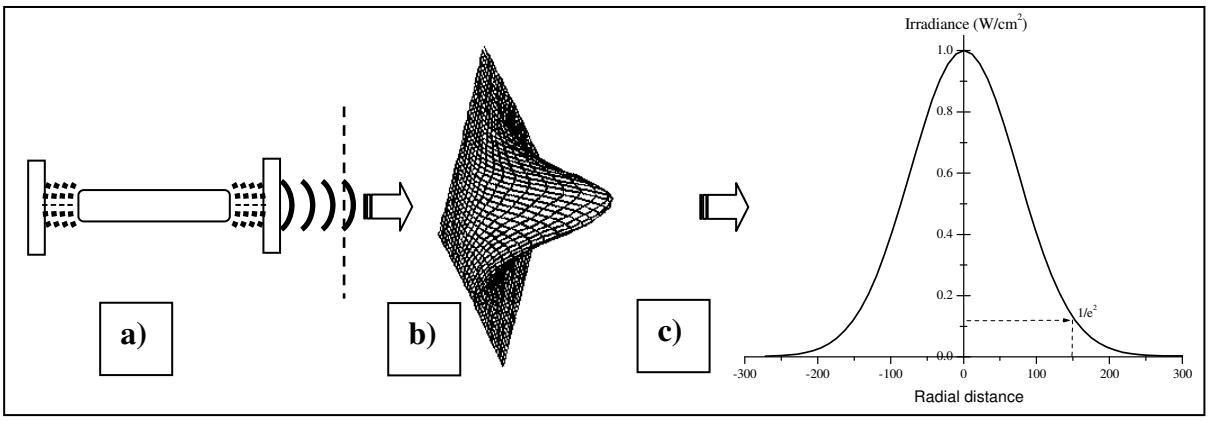

Figure 10 – Transversal energy distribution of a laser beam with a Gaussian profile. a) To visualize the energy distribution of a laser beam it is necessary to map the energy of the beam at different spatial position. This map is represented by figure b). If the beam is symmetric, it is possible to represent the same spatial distribution with a graph as presented in figure c).

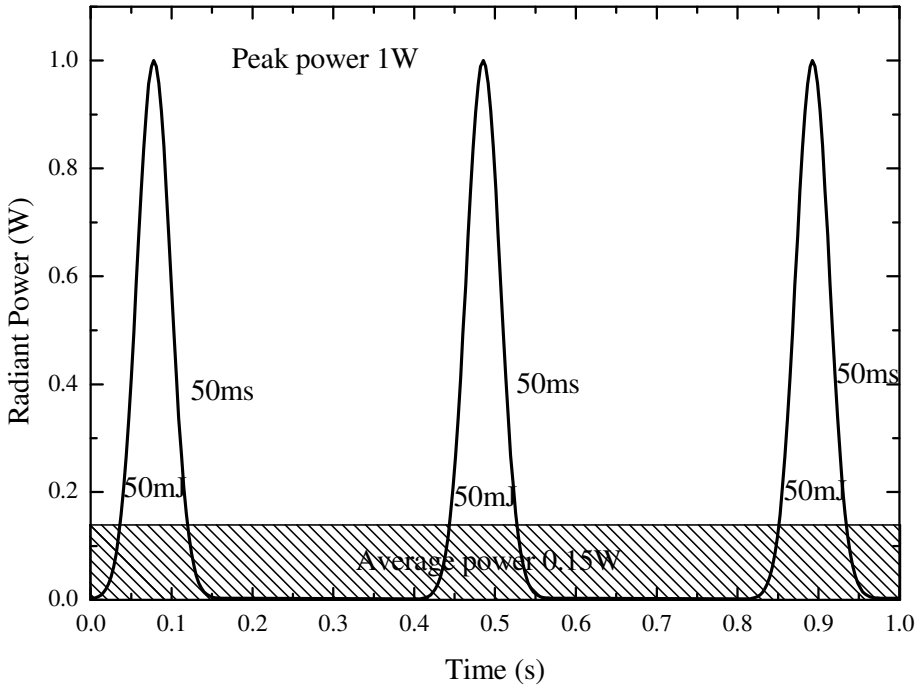

Figure 11 – Output beam of a pulsed laser. A laser emitting 3 Hz (3 pulses per second) with 50mJ of energy per pulse and 50ms of pulse width. The peak power for this condition is 1W and the average power only 0.15W. The radiant exposure and irradiance depends on the lighted area.

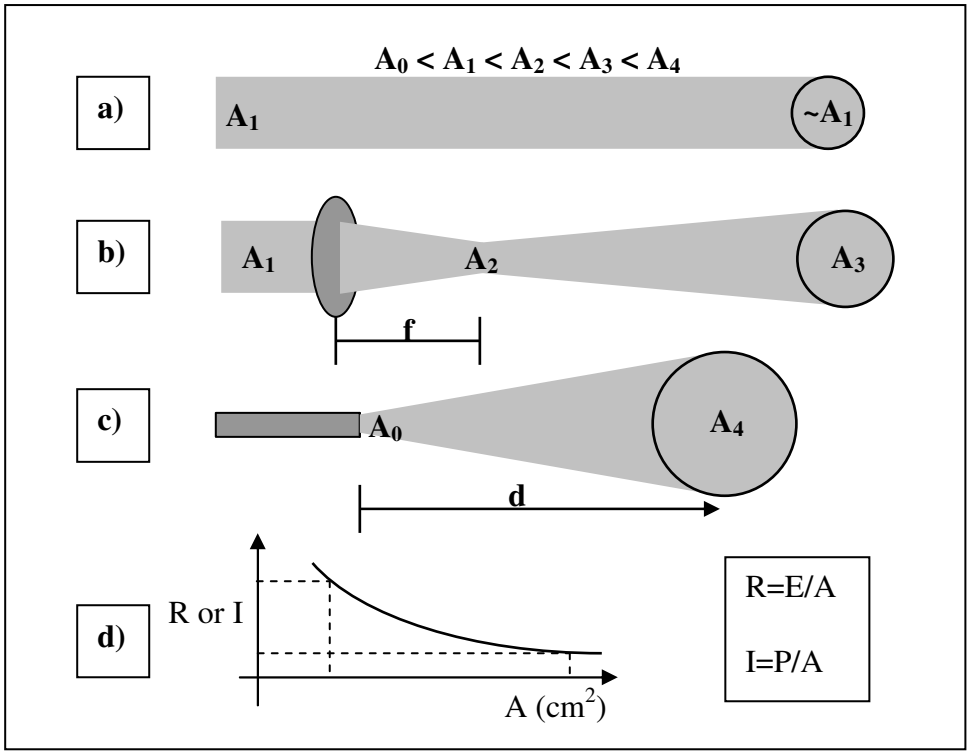

Figure 12 – Area of a laser beam for different irradiation conditions: a) unchanged laser beam; b) changed by a lens and c) by a fiber tip. a) The transversal area of an unchanged laser beam diverges a little, but for short distances (used in clinical practice), it can be considered equal for different distance values. b) If the laser passes through a lens the beam will converge to a focal point (f) and diverge again. c) Another example is a laser beam coupled to a fiber. d) Representation of the radiant exposure or irradiance as the transversal area increases.

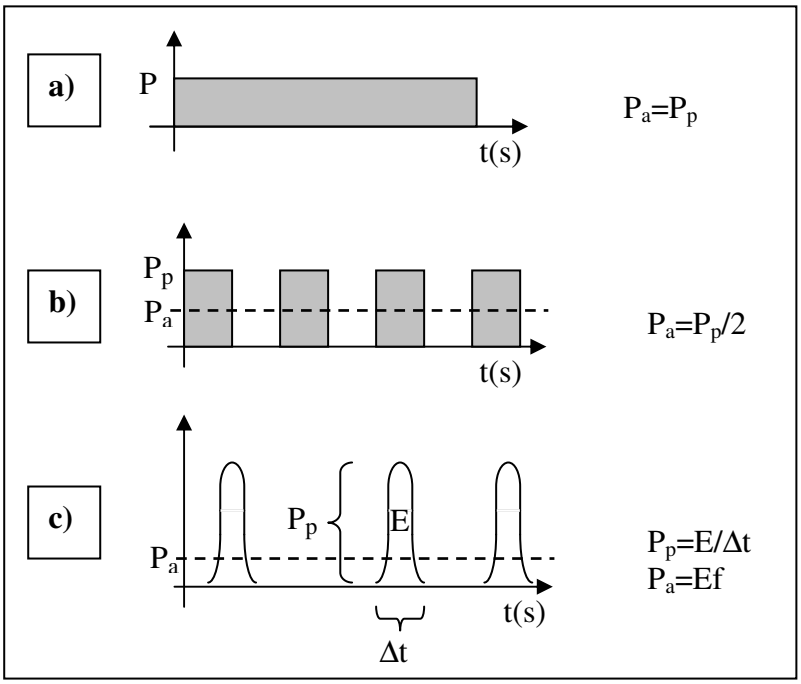

Figure 13 – Laser beam output. a) In a continuous emission the average power and peak power is equal and constant as the laser is tuned on. b) If the beam is interrupted (chopped), the average power falls down to half of the value of the peak power because the laser is 50% turned on and 50% turned of. c) In a pulsed laser, the peak power is calculated from the energy per pulse and pulse width, and the average power depends on the laser frequency.

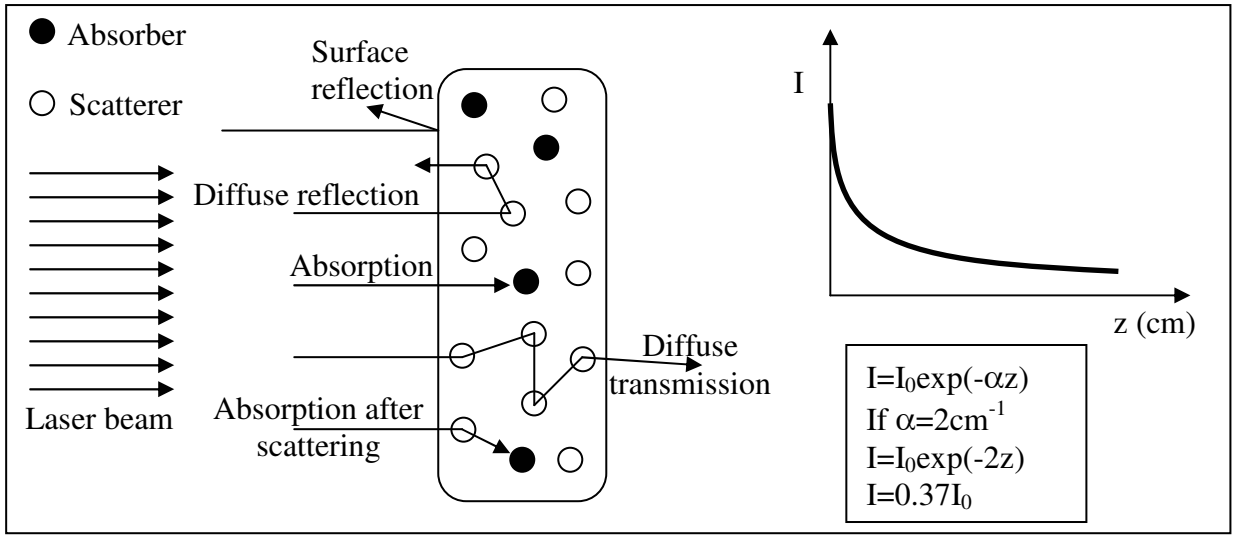

Figure 14 – Representation of the basic principles of the interaction of laser light with a tissue slab. After the interaction, part of the beam can be reflected at the material surface, named Fresnell reflectance. The photons that penetrate into the tissue can also be backscattered (diffuse reflection). The remaining photons will be absorbed by the chromophores into the tissue or pass through the slab, leading to the diffuse transmission (forward scattering).

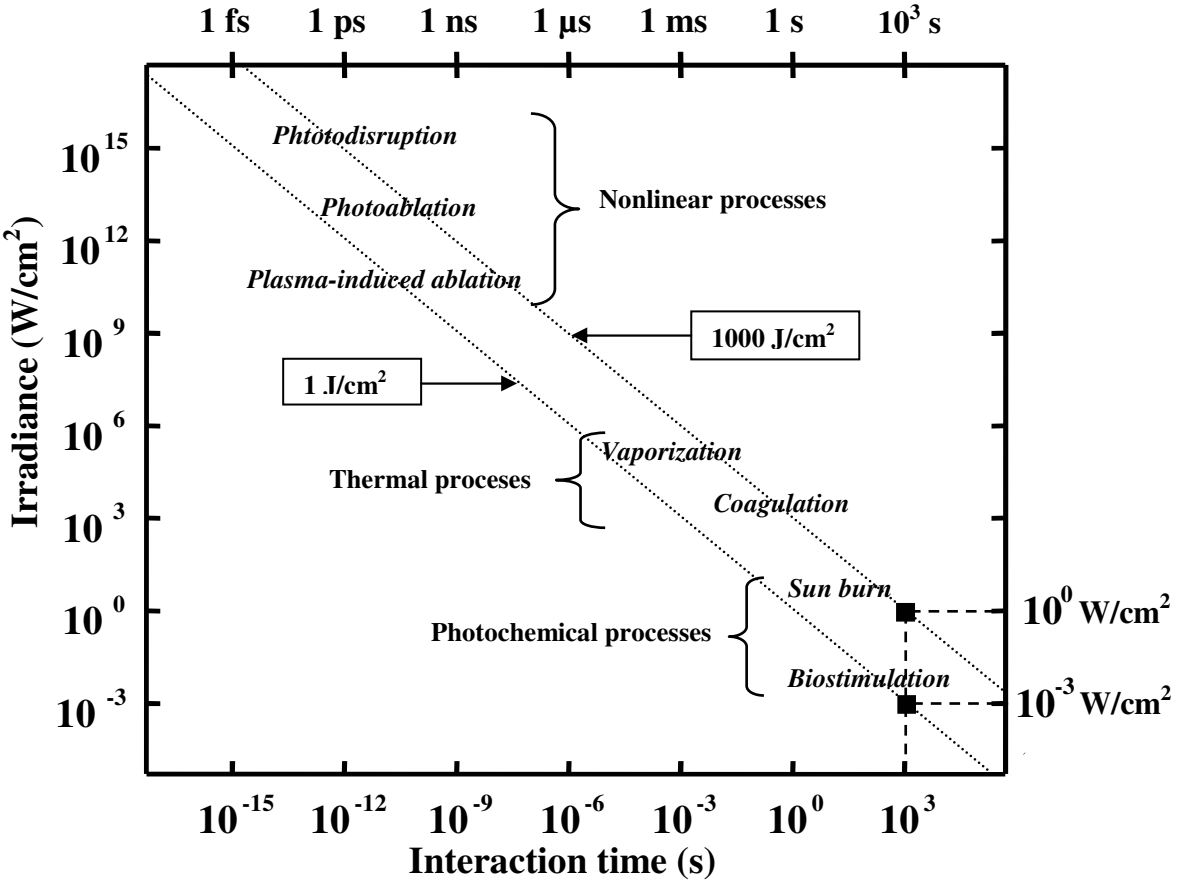

Figure 15 – The interaction of laser radiation will be determined by the duration of the interaction and the irradiance values. For example, photochemical interaction mechanisms are dominant for low irradiance, longterm exposure, while nonlinear effects occuring for short pulse, high irradiance exposure (adapted from [7]).

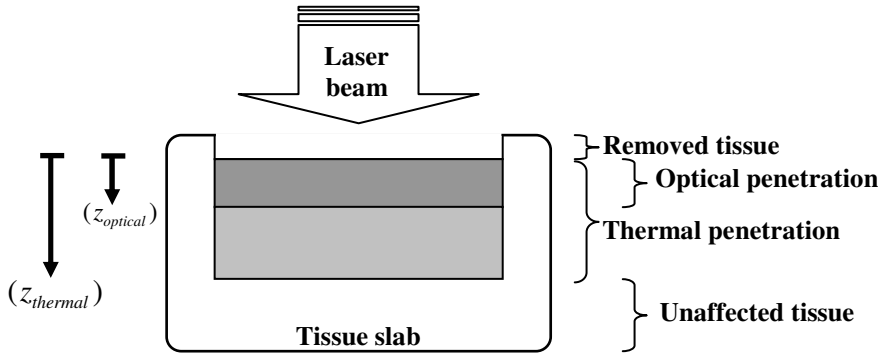

Figure 16 – One dimensional model of a laser irradiated tissue with the representation of a removed layer, the optical penetration depth $(z_{optical})$ and thermal penetration depth $(z_{thermal})$. The $(z_{optical})$ represents the depth that the photons reach. As the photons interact with the tissue and penetrate into the tissue, they will simultaneously produce tissue heating. This heat can propagate deeper into the tissue. The $(z_{thermal})$ represents the depth that the heat reached, which can be larger than the optical penetration, as exemplified in the figure.

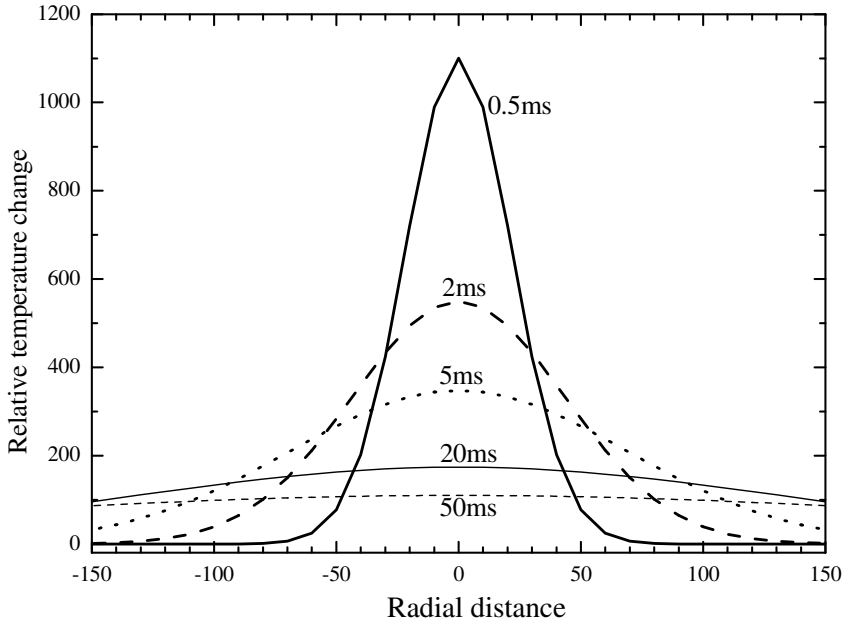

Figure 17 – Relative temperature progression at different distance from the irradiation site. The temperature profile can be visualized for different times after the irradiation has stopped: 0.5ms; 2ms; 5ms; 20ms; and 50ms. The temperature and time delay are only representative values for the temporal and spatial visualization; the real temperature and time depends on the irradiation parameters and on the thermal properties of the tissue.

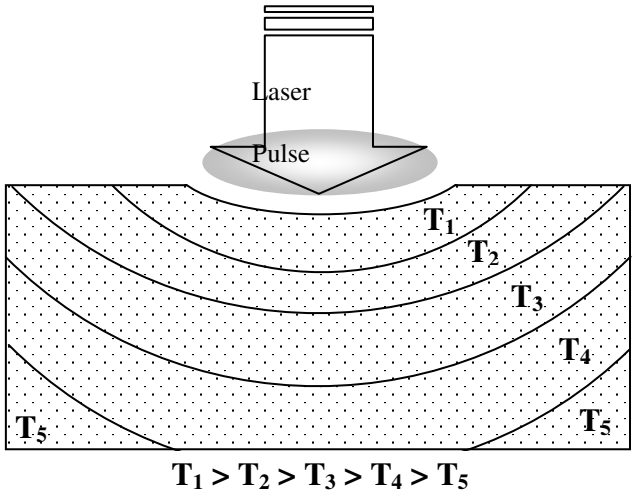

Figure 18 – Spatial distribution of temperature into a tissue block. In this diagram part of the tissue is removed (by vaporization, ablation), and the remaining tissue is submitted to thermal effects with the higher temperature localized in the first layer surrounding the removed tissue and the lower temperature in the deeper tissue. The time and temperature at each layer depend on the irradiation parameters and on the thermal properties of the tissue.

Table 4 – Dependence of biological effects on the temperature in heated soft tissues [3] and hard tissues [9]. These values are an approximation because the presence of these effects is not restricted to a specific temperature but also to a range of temperature and they are also dependent on the characteristics of the tissue.

Temperature (C)	**Biological changes in soft tissues**
45	Hyperthermia
50	Reduction in enzyme activity; Cell immobility
60	Protein denaturation, coagulation
80	Permeabilization of membranes
100-140	Tissue vaporization
150	Carbonization
Temperature (C)	**Biological changes in hard tissues**
140	Elimination of adsorbed water
200	Collagen denaturaion
300-400	Organic material loss
400-1000	Carbonate loss
200-800	Cyanate formation
800-1000	Cyanate loss
200-1000	Changes in Hydroxyapatite structure
600	(Ca_3PO_4)-β and (Ca_3PO_4)-α formation
1100	$Ca_4(PO_4)_2O$ formation
1300	Elimination of structural water
1300	Hydroxyapatite melting

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