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Teaching unit: Laser Physics and Medical Applications

DiFC - University of Palermo

BIOS4YOU AR 2.0

BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS THANKS TO THE USE OF AUGMENTED REALITY

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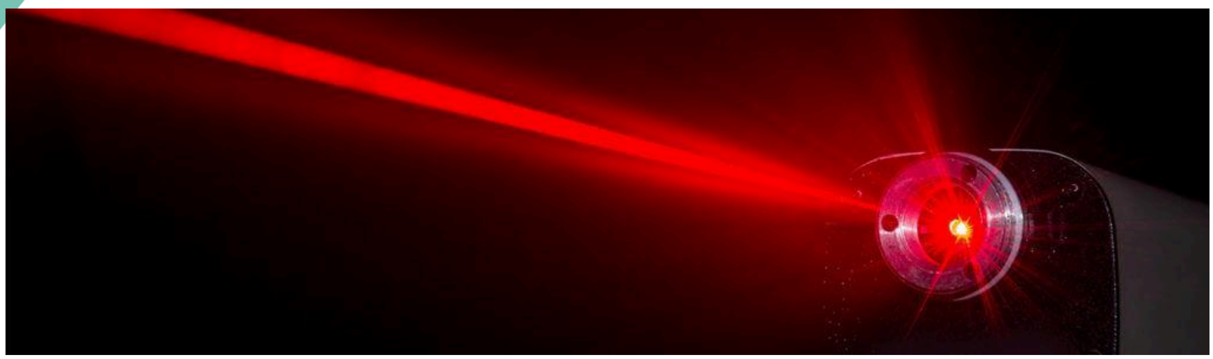

General topic of the learning path	Biophotonics and light-based diagnostic
Specific name of the learning unit	Laser Physics and Medical Applications
Age of the target users	14-18 years
Requirements for the learner	Basic knowledge of Mathematics, Physics, Chemistry, Biology.
Description of the learning unit	It will guide teachers and students through a multidisciplinary teaching/learning path to discover the basics of laser technology.
Subject: Parties involved	Biology, Chemistry, Physics, Mathematics, Engineering
Keywords	Light, laser, atom, Quantum Mechanics, AR, Visualization
Key qualifications, skills and knowledge that can be acquired	Problem solving, design thinking, reasoning, conceptual and practical knowledge of Physics, Chemistry, Mathematics,
Resources and didactic aids used	Web resources, virtual laboratories, research articles, scientific databases
Assessment criteria and evaluation	Different levels of knowledge of the concepts and skills achieved

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Introduction:

Light as a carrier of information

The light, as we all know, is a very important mean of exploring the universe. The color of light we see gives us important data. From the very beginning, we can discriminate the things we see by their colours.

The discussion about the origin and its structure has puzzled philosophers from the very beginning of history. Each of the early philosophers wrote their opinion about the nature of light. Only in the 17th century did the development of modern science put the discussion of this topic in a modern way with a mathematical theory.

We know that things come in particles (the matter is made of these) and in waves (the sailors and the musicians know it well…), so we have to understand if the light is made of particles or waves.

Isaac Newton, from the existence of the rays and their linear paths, said that light is made of different particles of matter (one for each color), which are emitted from the matter. The refraction is then explained by the forces that act on the particles of light during their transition through the separation surface of two media

Conversely, Christiaan Huygens wrote in its Traitè de la Lumiére (Treaty about the light) that light is made of waves which run in a very thin and special matter named ether, which is throughout the whole universe. The ether is an elastic medium made of very light particles of matter. This idea let him explain the properties of light (refraction, interference, diffraction, colors) in a very similar way to the well-known properties of sound. Like we can have from

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different wavelengths of the disturbance in the air/water/fluid, different sounds we have from the different wavelengths of the disturbance in the ether the different colors we can see.

The success of the ondulatory theory of Huygens in explaining led the scientific community to adopt his theory and to put aside the corpuscular theory of light.

The development of the study of the electrical and magnetic phenomena led James Clerk Maxwell to understand that light is an electrical and magnetic phenomenon. The light, in his vision, is a wave that goes through the space carried by that thin substance called ether.

At the beginning of the XX century, the physicists found that sometimes the light seems to interact with the matter in a continuous way as a wave, but in a discrete way as a particle or as a packet or quantum of energy. The photoelectric effect, the Compton effect, and the black body radiation are some of these phenomena. The explanation of these effects came from the development of quantum mechanics.

The finding of the LASER (Light Amplification by Stimulated Emission of Radiation) effect is another consequence of Quantum Mechanics, which perhaps is the physical theory with the greatest success.

This study aims to stimulate interest in a topic that lends itself well to a multidisciplinary approach in the field of STEM through the discovery of the basics of laser technology and to increase curiosity towards a topic whose research is at the forefront of research and has important implications in every field of modern life, including the well-being and health through diagnostics and surgical applications.

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Exploring the generation and use of laser technology is enhanced through the Augmented Reality exercise “Laser Technology and Medical Applications”, developed using Delightex Studio – Spaces (Marker). This AR experience guides students through five interactive scenes: three-level atomic systems with population inversion, stimulated emission and photon amplification, optical cavity design with mirrors, and medical laser applications (CO2, Argon, Nd:YAG). Six integrated quizzes provide immediate feedback, allowing students to visualize invisible quantum processes and connect atomic physics to clinical practice.

Section 1: Explore

Atoms

What is the structure of the atom?

The atom is the smallest part of matter that has chemical properties. In 1 gram of Hydrogen, there are $6,022 \cdot 10^{23}$ atoms. It contains the three types of elementary particles that constitute matter. The protons (positively charged particles) and the neutrons (neutral charged particles) are packed in the nucleus, while the smaller electrons (negatively charged particles) orbit around the nucleus in regions called electron shells or energy levels, creating a cloud of negative charge that balances the positive charge of the protons and determines the atom’s chemical properties. The mass of the atom is the sum of the masses of these particles, but because the electrons are lighter only the 0,06% of the mass of the atom is electronic.

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However, the electrons give the atom all its chemical properties. The number of electrons is the Atomic Number of the element. Quantum Mechanics tells us that the electrons in the atom may have only some energies in a discrete way.

The energy of the *n*-th level is given by the formula

$$E_n =- hcR_\infty \frac{Z^2}{n^2}$$

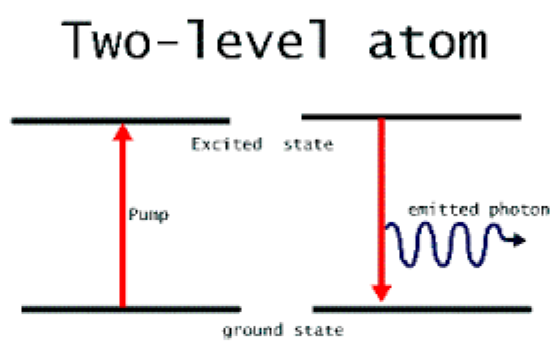
where *h* is the Planck constant, *c* is the speed of light, R_∞ is the Rydberg formula, and *Z* is the Atomic Number of the atom.

When an electron goes from a higher level of energy to a lower level, it emits a quantum of electromagnetic energy (a photon). The energy is the difference of the energies of the levels involved, and it is emitted with a frequency *f* given by the formula

$$f = \frac{E_2 - E_1}{h}$$

being E_2 the energy of the higher level (i.e. the starting level of the electron) and E_1 the energy of the lower level (i.e. the destination level).

This kind of emission is called ***spontaneous*** or ***radiative emission***.



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In order to fully understand the of the dynamics of this kind of emission is important to recall some characteristics of the constitution of the atom.

The electrons obey the laws of Quantum Mechanics that tell us that

- we can't find the position and the momentum of the particles with infinite precision (**Heisenberg Uncertainty Principle**)

- we can only know the probability of finding a particle in a certain position in space through the use of the **Schrodinger** equation. The solutions of this equation give us the probability as a function of the space coordinates. As a result, we can visualize the zone of the space where the probability of interaction with a particle is non-negligible.

In the case of the electrons in the atom, the solutions of the Schrodinger equation are called orbitals.

The **Pauli Exclusion Principle** allows only two electrons (one for each direction of the electronic property called spin) to occupy one orbital i.e. to satisfy the conditions of the Schroedinger equation.

The energy level structure of the atom and the transitions between them depend on these rules.

The laser effect

The word laser is the acronym of Light Amplification by Stimulated Emission of Radiation.

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The reason of this name comes from the fact that when we have some electrons in a higher level than the level of minimum energy, an electromagnetic wave of the right frequency may stimulate the decay of the electrons onto a lower level. The amazing thing in this situation is that the emitted electromagnetic wave has the same frequency and phase and direction as the incident stimulating wave.

This means that the incident light is highly reinforced because

- the same direction of emitted light leads to a very low spreading of the light ray (**collimation**)
- the same phase implies that there is no interference between the photons (**coherence**)

In order to achieve a highly powerful stimulated emission, we have to pump a large number of electrons into the same level and let them decay onto the lower level together at the same time.

The problem in this situation is that if we pump some electrons into a higher energy level by stimulated absorption of energy, the atoms emit at the same rate as the pumping occurs. We have to "lock" the electrons in a level that doesn't decay at the same rate as the pumping.

The laser emission

The laws of Quantum Mechanics applied to the electronic levels tell us that the rate of decay is not the same for each pair of levels. Each transition has a characteristic decay time. Some transitions have a very

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short decay time (i.e. the electron stays in the upper level for a minimal time) while other transitions may not occur for a long time.

A system with a lot of identical atoms in a certain time $\boldsymbol{N_2}$ (in a volume unit) atoms have at least one electron in the level **2,** which has a higher energy than the corresponding level **1** (lower energy) where the electron can go.

The number of atoms ΔN_2 that do this transition (**2** to **1**) in a certain amount of time Δt is given by the formula

$$\frac{\Delta N_2}{\Delta t} = -AN_2$$

where the number ***A*** is called the Einstein coefficient and is the inverse of the mean lifetime by spontaneous emission τ_{spont} of the electron in level **2**.

After the lifetime τ_{spont} the mean number of atoms in the level **2** is $\frac{N_2}{e}$ where $e = 2,71828...$ is the Neper number.

When the atom is hit by an electromagnetic wave whose frequency is the same of that of the atomic transition, the photons of the wave force the atom to undergo the transition.

The fundamental difference between stimulated emission and spontaneous emission is that the emitted photon has the same phase and direction as the incident wave.

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Obviously, we obtain an enhancement of the radiation if the number of electrons (population) in level **2** is higher than the population of level **1.**

The three-level atom

An effective configuration to achieve a laser device is to use not only two levels (the level of the laser transition) of an atom, but a three-level configuration in order to achieve the so-called population inversion in the high level from which the stimulus of the incident wave let the atoms emit at the same time.

In order to achieve the population inversion, we have to pump the electron in the level **1** to the level **2** via an electromagnetic wave of the right frequency that gives to the atoms the energy to jump to the higher level.

If we have only two levels, the electromagnetic wave pumps the electrons in the lower level to the higher level at the same rate that the wave stimulates the emission from level **2** to level **1**. We need to “trap” the electron in the higher level.

Using three levels of an atom, we can pump the electron into a high level (level **3**). The electron decays rapidly in an intermediate level (level **2**) and stays there until a wave of the right frequency stimulates the decay on level **1.**

This procedure needs two different stimulating waves with different frequencies. The first (pumping radiation) has the frequency $f_{31} = \frac{E_3 - E_1}{h}$

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while the second one (stimulating radiation) has the frequency

$$f_{21} = \frac{E_2 - E_1}{h}$$

The device will be set in a “ready” state by the inversion of population caused by the pumping wave. When we need the laser emission, we let the stimulating wave go through the material, and the electrons in the second level decay all at once, giving a strong emission of radiation.

In order to fully use the stimulating incident wave in the laser device, the active material is located inside mirrors.

These mirrors make a resonant cavity that enhances the radiation emission.

Out of the active material, like ruby in modern technology, diode lasers are also used.

Section 2: Execute

In order to understand the laser device, we have to focus on the main features of the laser emission:

- **Monocromaticity:** All the photons emitted have the same frequency
- **Coherence:** The emitted wave has the same phase in each of its part.
- **Directionality:** The emitted wave has a very well-defined direction with very little spreading
- **Brilliance:** The emitted power over the surface unit and solid angle is very high

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- **Short impulse:** The light emitted may have a very short duration

TThe Monochromatic feature of the laser is perhaps the most important one. It has several important applications in biotechnology. For example, it allows for the transfer of power only to the selected tissue. In order to do so, one only needs to choose a laser device that has the emission frequency in the range where the biological tissues are sensitive (i.e., a specific wavelength that is strongly absorbed by the target tissue, such as hemoglobin, melanin, or water, depending on the application).

The **Coherence** and **Directionality** allow to focus strictly on the selected position.

The **Brilliance** enhances the transfer of power to the tissues.

The **Short impulse** allows to avoid to transfer too much energy to the tissues.

In the AR exercise, students explore laser generation through sequential scenes showing atomic excitation, stimulated emission, and optical cavity function, then apply this knowledge by answering quizzes about appropriate laser selection for different medical procedures.

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Section 3: Enhance

As an example, the students will be able to choose the right atomic levels to use in order to calibrate a laser that can destroy tumourous skin cells.

The student will choose the right frequencies knowing that the cells to be destroyed are sensitive to specific frequencies.

The main types of lasers currently used in cancer treatment include:

- Carbon dioxide (**CO2**)
- Argon (**Ar**)
- Neodymium: yttrium aluminum garnet (**Nd: YAG**)

Doctors and other health experts who use these lasers need special training in how to use and safely handle them.

Carbon dioxide (CO2) lasers

CO2 lasers don't go deep into tissues like Nd: YAG lasers. They can cut or vaporize (dissolve) tissue and cause little bleeding. They do little damage to the surrounding or deep tissue. They are used to treat pre-cancers and some early-stage cancers.

Argon lasers

Argon lasers, like CO2 lasers, only go a short distance into tissue. They are useful in treating skin problems and some types of eye tumors. Sometimes, they are used during colonoscopies (tests to look for colon cancer) to remove polyps before they become cancerous. They can also be used with light-sensitive drugs to kill cancer cells in a treatment known as photodynamic therapy (PDT).

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Another way they can be used is to help stop bleeding by sealing blood vessels in patients who are getting radiation therapy for certain types of cancer. This might be needed because sometimes radiation therapy can damage the blood vessels near tumors, causing them to tear and bleed.

Nd: YAG (Neodymium: Yttrium-Aluminum-Garnet) lasers

Light from this laser can go deeper into tissue than other types of lasers, and it can make blood clot quickly. Nd: YAG lasers can be used through thin flexible tubes called endoscopes to get to hard-to-reach parts inside the body, such as the esophagus (swallowing tube) or the large intestine (colon). This light can also travel through flexible optical fibers (thin, clear tubes) put into a tumor, where the light's heat can destroy it.

Treating cancer with lasers

Lasers can be used in 2 main ways to treat cancer:

- To shrink or destroy a tumor with heat
- To activate a chemical (a photosensitizing agent) that kills only the cancer cells

Lasers can be used alone or with other cancer treatments, such as chemotherapy (chemo) or radiation therapy.

Shrinking or destroying tumors directly

The CO2 and Nd: YAG lasers are used to shrink or destroy tumors. They can be used with thin, flexible tubes called endoscopes. Endoscopes let doctors see and work inside certain parts of the body that could not otherwise be reached except by major surgery. Using an endoscope also helps position the laser beam to hit its target accurately.

Here are some examples of how lasers treat cancer or pre-cancerous

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conditions:

- Colorectal polyps: Lasers can be used to remove small growths in the colon and rectum that might become cancerous, called polyps.
- Pre-cancers and early cancers: Lasers can be used to treat some pre-cancers of the skin and cervix, and early cancers of the skin.
- Advanced cancer: Lasers might be used to treat cancers causing a blockage in the airway by destroying a part of the tumor.
- Brain tumors: Laser-induced interstitial thermotherapy (LITT) can be used to treat some brain tumors. It uses heat to help shrink tumors by damaging cells or taking away the things they need to live (like oxygen and food).

Lasers using photodynamic therapy

For most types of photodynamic therapy (PDT), a special drug called a photosensitizing agent is put into the bloodstream. Over time, it is absorbed by body tissues. The drug stays longer in cancer cells than in normal cells.

Photosensitizing agents are turned on or activated by certain types of light. When cancer cells that contain the photosensitizing agent are exposed to light from an argon laser, it causes a chemical reaction that kills them. Light exposure must be carefully timed so that it's used when most of the agent has left healthy cells but is still in the cancer cells.

PDT is sometimes used to treat cancers and pre-cancers of the esophagus, bile duct, bladder, and certain kinds of lung cancer that can be reached with endoscopes.

It is also being studied for use in other cancers, such as the brain, pancreas, and prostate. Researchers are looking at different kinds of lasers

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and new photosensitizer drugs that might work better.

Conclusion:

In this unit, we explore the main features of the laser devices. We analyze the characteristics of the matter and the atoms that make it feasible to get the laser light.

We see how the three-level atom configuration is the better one in order to create the population inversion. The population inversion acts as a reservoir of electrons. When stimulated by the right frequency, all the electrons emit as a whole with the same frequency and phase.

This kind of emission allows focusing the electromagnetic wave in a small area and producing a short impulse with the desired amount of power. The following heating of the hit matter might be used to melt and weld materials or in biomedical applications to destroy ill tissues or to cauterize.

The students, via the use of the AR, can explore all these features in order to have a clear idea of the physical processes involved in the laser effect and in the construction of the laser devices.

Students apply the acquired knowledge by evaluating appropriate laser choices for clinical scenarios, including tissue penetration depth, surface treatments, and photodynamic therapy applications.

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Phase	Description
Explore	- Research and Discovery: Quantum mechanics and atom configuration
	- Content Development: Atomic levels
	- Needs Analysis: Electromagnetism, waves, semiconductor, diode, anatomy.
Execute	- Curriculum Implementation: Knowledge check
	- Interactive Exercises: Tuning a laser devices
	- Feedback Collection:
Enhance	- AR Integration: Building a laser device
	- Interactive Learning: Tuning up a laser device to operate
	Gamified Content: - **Points and Badges**: a dynamic scoring system where they earn “points” or none at all by answering the questions - **Quests and Levels**: The question's difficulty level allows to manipulate the concepts. - **Rewards for Exploration**: The earning points system encourages them to apply their knowledge to gain more points in each phase and, at the end, they can create a ranking list with the points earned. - **Collaborative Gamified Tasks**: They can work together in order to achieve the best results.
	AR-Based Assessments: Replace traditional tests with AR-based evaluations.

References:

Atomic structure and levels: https://www.youtube.com/watch?v=uiwRhxoz5sI

Diode laser: https://www.youtube.com/watch?v=_I4fyOtyvPg

Cancer treatment:
https://www.cancerresearchuk.org/about-cancer/treatment/other/laser-treatment

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