Lecture 3: Laser Manufacturing

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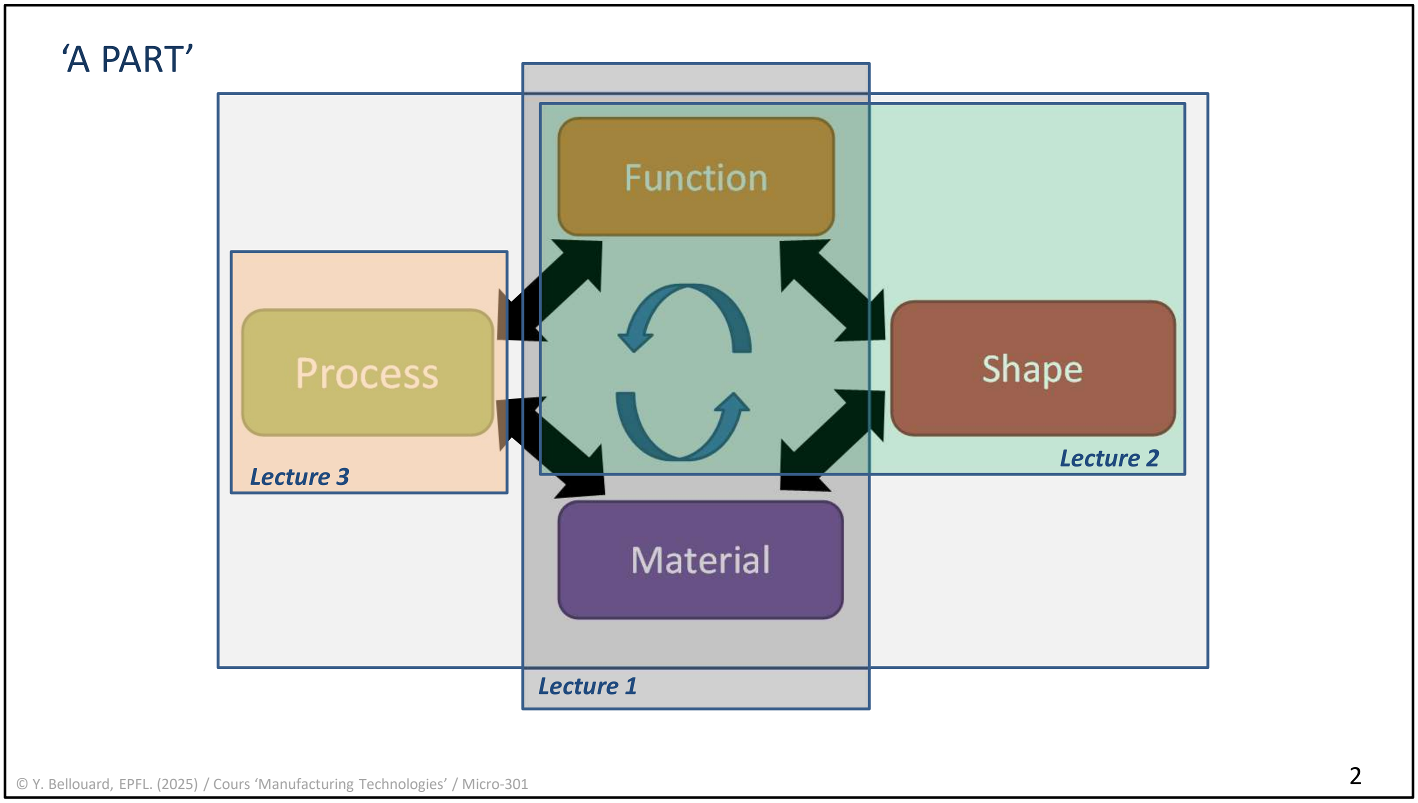
EPFL



In the first lecture, we have seen that in the process of designing an object, there is an intimidate relation between a material and the desired function of an object. We saw some methodology for optimizing the choice of a material in connection with a specific task.

In the second lecture, we focus specifically on shape and functionality, and more specifically on the role of surfaces.

In this third lecture, we start reviewing manufacturing process, by discussing laser manufacturing.

Today's Learning objectives

- Problem statement
- An introduction to some basic concepts in optics and light-matter interaction (Lorentz model)
- Absorption and refractive index
- Transferring energy to a material with a laser

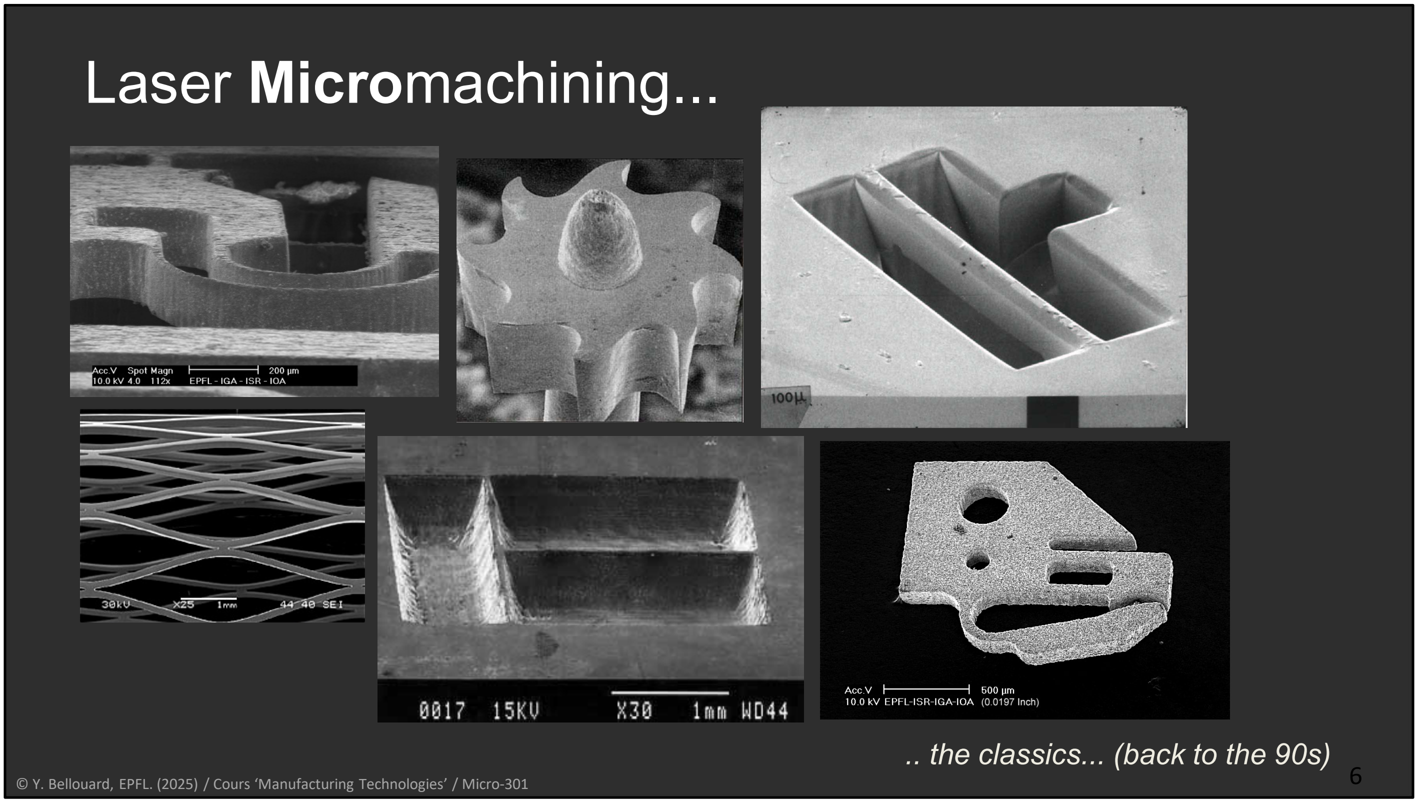
This lecture aims at giving you a sufficient background to understand generic principles around laser manufacturing and more specifically, laser-matter interaction.

The objective is to provide tools for you to be able to appreciate key differences between the numerous laser-based processes that exist.

Quiz

- What applications of lasers do you know in manufacturing?

Discussion in class



The pictures above are just a few illustrative examples of micromachined components. From top to bottom:

- **Top left and right:** microgripper done at EPFL in 1998 – at that time a research project. It was machined using a Nd-YAG nanoseconds pulse laser. The microgripper is made of a shape memory alloys (Ni-Ti Alloy). Such structures are not more commonly done industrially.

- **Middle left:** tubular structures (here a medical product - a stent) machined with a pulsed laser out of a metal.

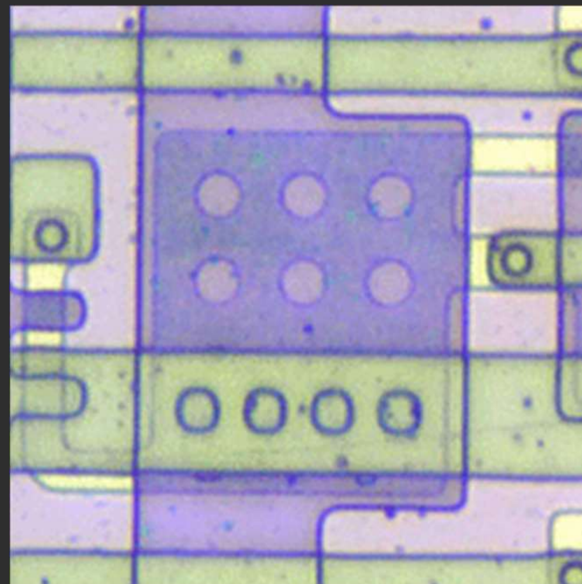
- **Middle-center:** micro-gear machined using an excimer laser.

- **Middle-right:** channels made in a polymer

- **Bottom-left:** waveguides written in the bulk of glass using a femtosecond lasers. Notice the three-d structure.

- **Bottom-center:** cuvettes obtained by ablating the surface of a metal realized using a pulsed-nanosecond laser.

- **Bottom-right:** branching fluidic channels made by femtosecond laser exposure followed by a chemical etching step.

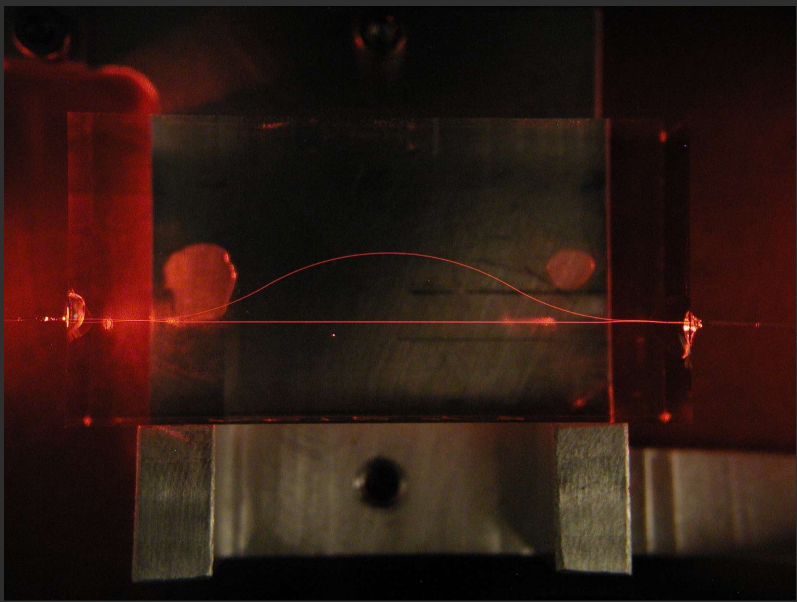


(source Amplitude lasers / KIMM – Corée)

The video illustrates the selective removal of a layer covering other electronics layers.
Just one layer is removed, without affecting the layers underneath.

It illustrates the capability of some laser-processes to be selective.

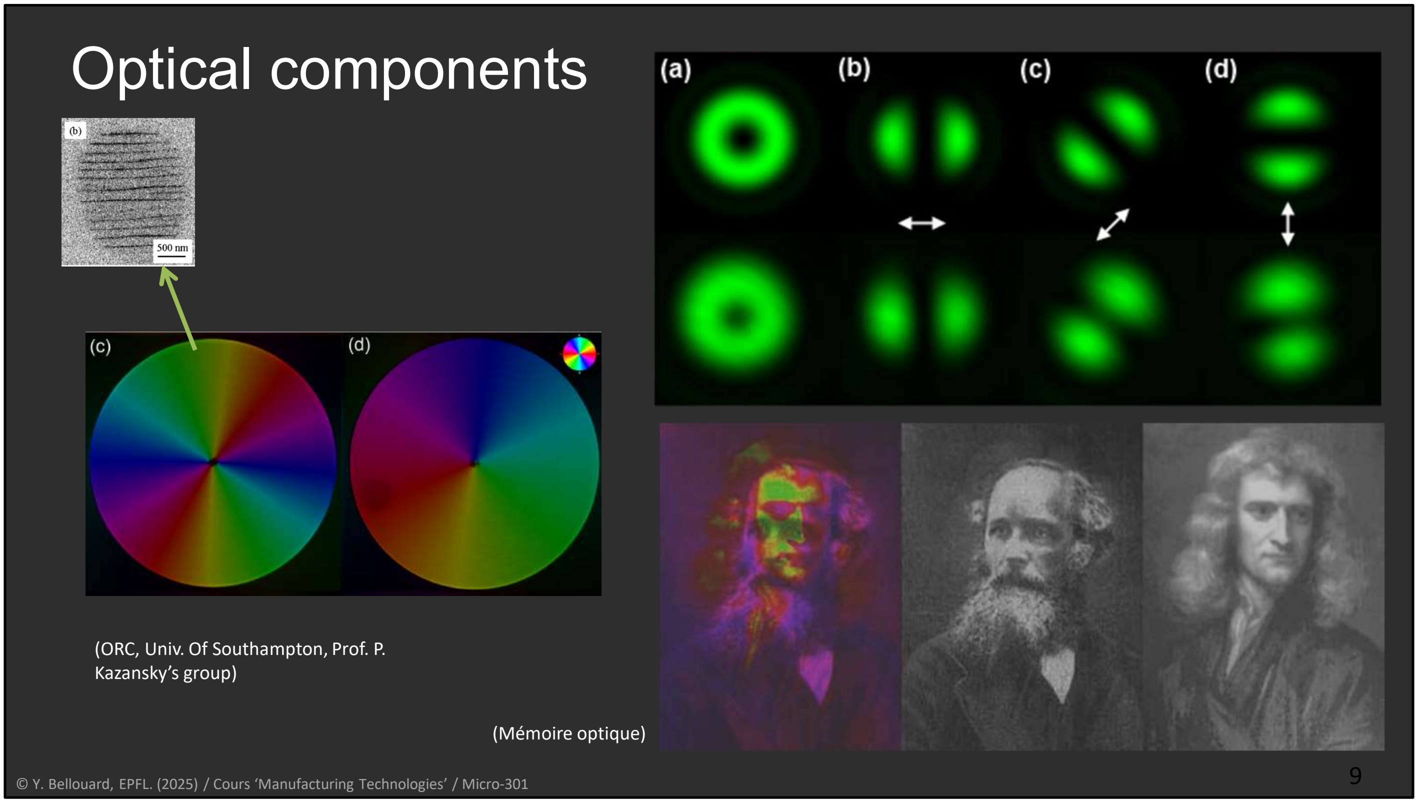
'Optical circuit'



(Source Translume)

This example illustrates waveguides written in the *bulk* of a glass substrates. The waveguide can be seen as 'light pipe' that guides an optical wave. Waveguides can be combined to form complex functions. The one above makes two optical beams interfering.

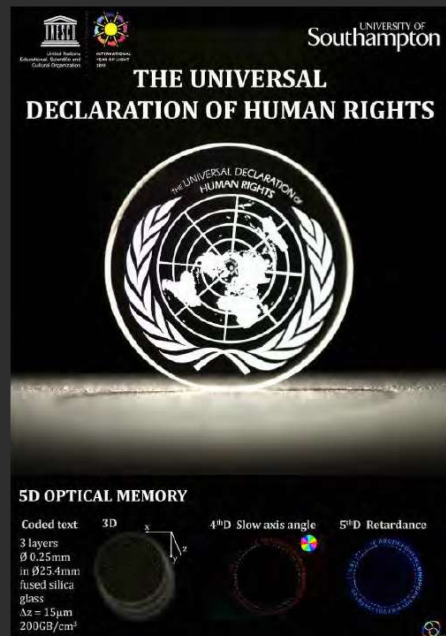
Here, it illustrates that one can some particular laser processes can be used to structure materials in their volume, and hence below the surface. What is remarkable is that the laser goes through the material without doing anything, except at the point where it is focused where something happens and where the materials get modified and only there.



In this other example, a laser is used to encode information also directly in a glass substrate, hence below the surface like in the previous case. This is done using femtosecond laser to create micro-size structures having the size of a micron. While the spot-size is one micron, one can observe self-organized structures (parallel nano-planes) appearing inside the laser focus.

Every pixel consist of structure formed of self-organized nano-planes (see in the top left) that create local polarization properties. These pixels can be combined for engraving complex optical devices or recording data, like illustrated with the portraits of Maxwell and Newton. The portraits are about 100 microns.

Eternal memory



Source: Peter Kazansky Univ. de Southampton

https://www.microsoft.com/en-us/research/project/project-silica/

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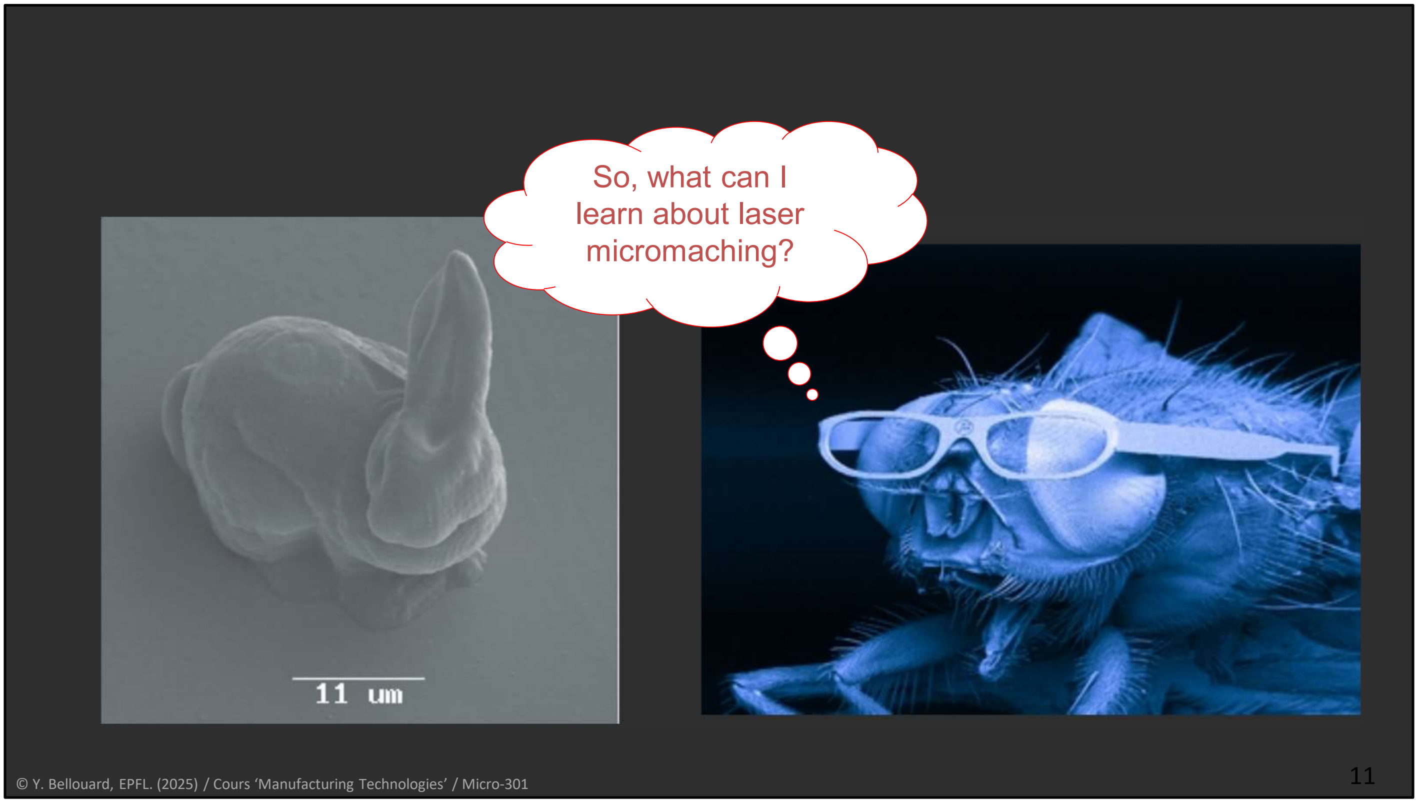
Some further illustrations of the use of this principle for recording data. The substrate has the size of a five Swiss franks coin. The books of Newton are recorded into the three little disk, around the label 'Newton opticks'.

On the right image, the universal declaration of the human rights is written at the North pole on the map.

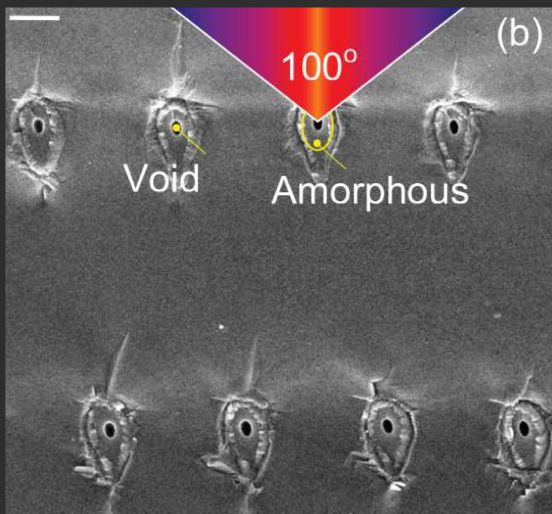


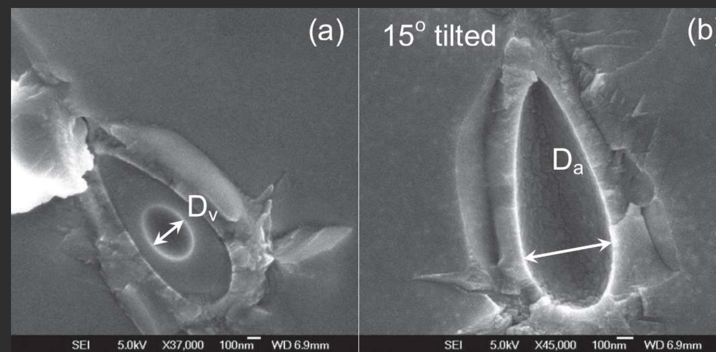
The little bunny has been made using three-dimensional localized laser-induced polymerization. In this case, it resembles a lithographic process, but *without* masks, and in three dimensions.

This is obtained using so-called 'non-linear absorption' processes that we will be described later in this lecture. The picture on the left illustrates an example of achievable resolution of laser machining processes.

The spectacles fitted on a the fly, shown on the right image, are similar polymeric structures made using non-linear processes.

The weirdness starts...

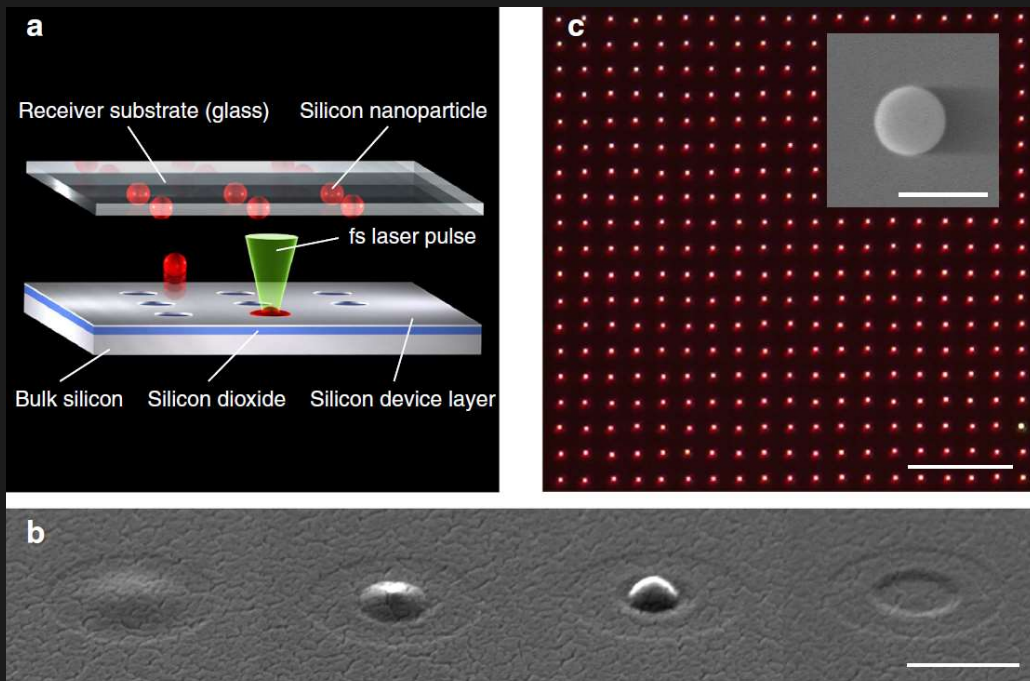




S. Juodkazis, et al., Phys. Rev. Lett. **96**, 166101–4 (2006).

In this example, a laser is used for creating 'nano-scale explosion' *inside* a sapphire substrate. These explosions resemble cavitation process. Around the explosion site, the material has been submitted to extreme pressures (similar to extreme pressures found in the Earth mantle), leading to novel material phases formation.

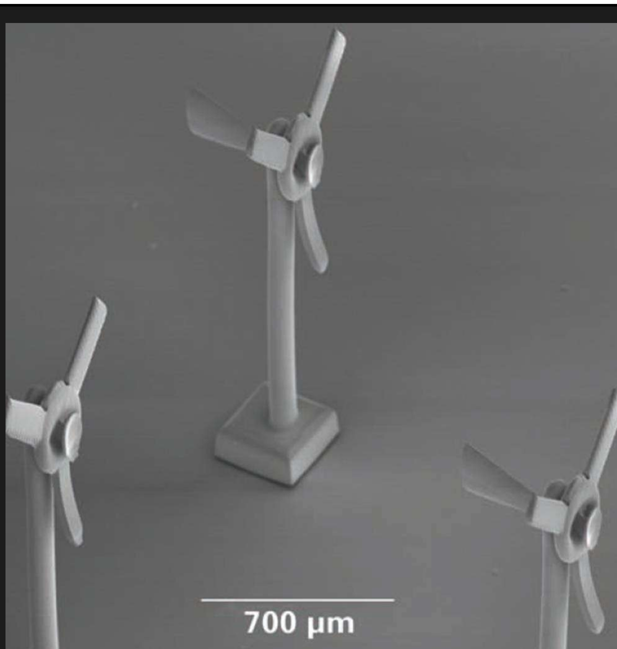
This process is more for research purposes and materials discoveries.

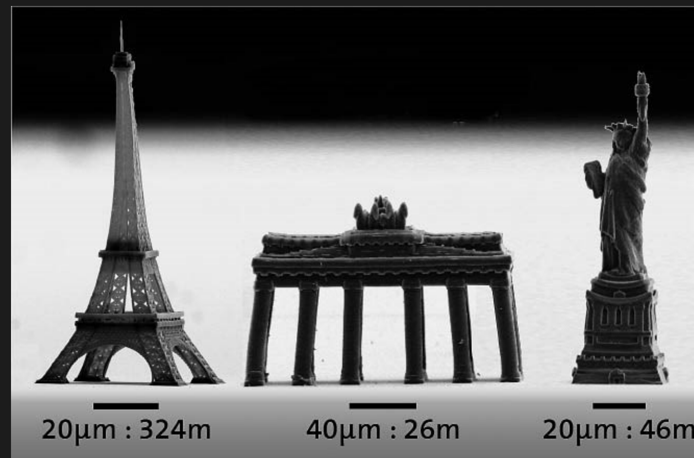


Chichkov, Nature Comm. (2015)

This example illustrates the use of laser to deposit through a laser-induced forward transfer of nanoparticles. In this example, silicon nanoparticles are 'ablated' by light from a substrate and propelled towards a received substrate (glass substrate).

The laser goes through the glass substrate as well.





(source Nanoscribe)

Examples of micro-scale windmills and micro-replica of famous monuments made by 3D lithography using multiphoton polymerization. In essence, it is a micro-scale 3D-printing technique.

Laser in manufacturing

- **Removing material**… (cutting, ablating, etc.)
- **Transforming material**… (annealing, polymerizing, etc.)
- **Growing material**… (Promoting Chemical Vapor Deposition, Pulse laser deposition, etc.)
- **Additive manufacturing**… (Powder bed fusion, etc.)
- **Joining materials**… (welding)
- **Surface treatment**… (Oxidizing, hardening, etc.)
- **Surface texturing**…

Laser are present in a considerable number of manufacturing sectors where they fulfil various tasks:

1/ Removing materials, which is what most people are aware of when discussing manufacturing with lasers. We will see during the lecture that removing materials using lasers can be done in different manners. One is to melt locally materials that is latter 'blown away' from the solid part. Another one is to ablate materials. In such case, the transformation of matter is more complex and limited or no liquid phase is formed. Finally, two-step processes involving a laser exposure, followed by post-treatment steps (annealing, polymerization, etching, etc.) are also often used, in particular in the context of 3D micro-manufacturing.

2/ Transforming materials. Lasers are very used in multiple processes where the objective is to transform the structure of a material. For instance, laser are used for annealing thin films or materials locally. They are also used for inducing polymerization reactions, localized densification in glass or to create a certain stress field in the bulk of the material.

3/ Joining materials. Laser are widely used for welding or brazing two materials together. This is one of the most important industrial applications.

4/ Surface treatment and surface texturing. Their, they are used for inducing localized oxidation reaction, for hardening surfaces ('laser-shot peening') or for texturing surfaces, eventually with nanoscale features.

A few examples…

- Surface hardening (laser shot peening) (‘écrouissage’)
  - https://youtu.be/VcTQN-Sz5rM
- 3D Nanoprinting (laser photopolymerisation)
  - https://youtu.be/wThtfAtB5U8
- Cutting
  - https://youtu.be/3I2maA2zDJM
- Additive manufacturing
  - https://youtu.be/Fr_PneeyO34

Here are a few illustrative videos examples of various use of lasers in industry. Notice the different types of processes across scales.

Notice also that laser machining is not restricted to planar substrates.

Questions?

- **Why so many different types of lasers ?** i.e. Role of the wavelength?
- **Pulsed** or **not pulsed?**
- **Short** or **long** pulse**?**
- Can we selectively remove matter?
- Work material inside their volume?

As we have seen in the various examples, there are a large number of applications for laser technologies. Equally numerous are the different types of lasers with different wavelengths, different pulse characteristics, duration, etc.

Key questions are therefore to understand on one can make an educated choice between different wavelengths, to appreciate in which situation long or short pulses are needed, to further understand why it is possible to work in the volume of the part to be machined, etc.

In the following pages, we will provide some insights for answering these questions.

What all this process have in common?

- Light…
- Transfer energy to the material…
- 'Material absorbs the incoming energy'

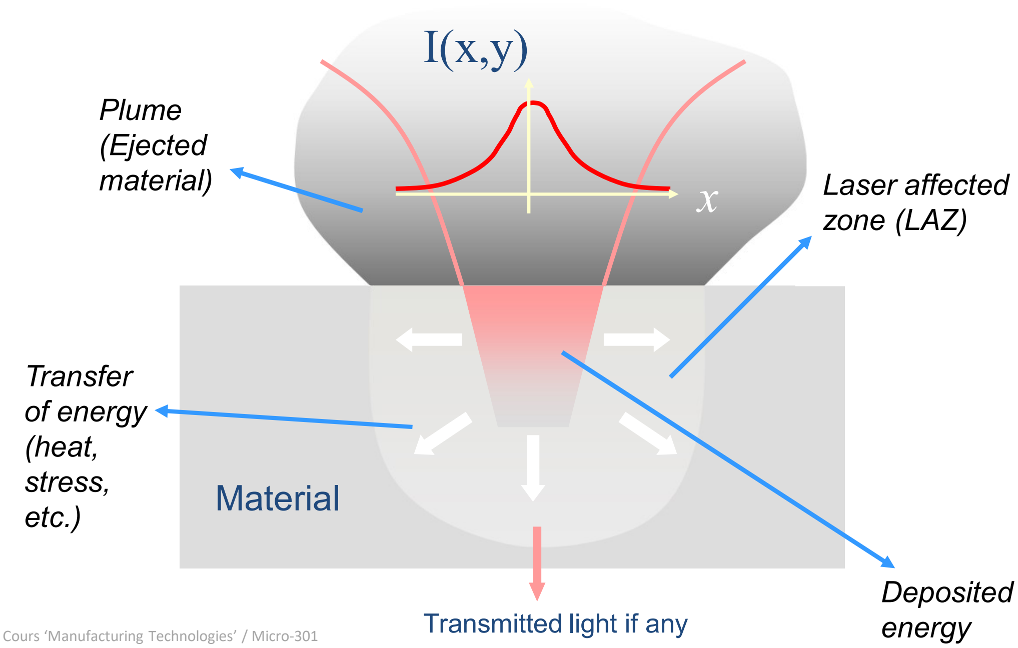
Lasers generates optical waves to transfer energy or to pass energy through a material.

All or part of this energy is eventually absorbed in the material according different modalities that may induce different types of material responses.

In manufacturing, we are concerned with the fundamental transformations occurring in the material and how they can be used of fabricating particular shapes or for transforming materials.

Optical waves generated by lasers have particular properties that we will summarize in the following slides.

Schematic of laser-matter interaction



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The schematic above describes a very generic scenario when laser light penetrates in a material and when linear absorption phenomenon are taking place.

Typically the light is focused on or within the material. As it penetrates through, a portion or all of the incoming light gets gradually absorbed. This 'deposited energy' is then dissipated in various ways. Some of this deposited energy may be converted into heat that may vaporize the material to generate a **plume** (or ejecta). This energy may also dissipate in the form of mechanical energy, eventually creating stress wave.

The broad region in which the effect of the laser can be seen is called the '**Laser Affected Zone**' (LAZ). Note that this zone can be smaller or larger than the zone under optical exposure. In classical linear-absorption regime laser machining, the LAZ is typically broader than the zone that was exposed to the light emitted by the laser.

As it will be seen in the following slide, the laser distribution of energy around a laser spot has a **Gaussian intensity profile** in most cases. It is maximum in the middle and decays following a Gaussian law on the edges.

Note that in the scenario where some of the material is vaporized and ejected away from the substrate, the laser beam itself passes through this ejecta (that resembles a 'cloud' of particles) and may further interact with this cloud. It is therefore a dynamical process where the laser interacts with the byproduct of its own interaction with the material surface.

Laser-matter interaction

- A dynamical process: “how the energy deposited by the laser is ‘digested’ by the material”

Molecular bond breaking (Ionization)
↓
Ablation

Heat transfer to the material (phonons for dielectrics, electrons for metals)
↓
Melting
↓
Vaporization

Pressure wave
↓
Stress
↓
Plastic deformation
↓
Fracture

Laser-matter interaction can therefore be seen as a dynamical process in which the incoming energy provided by the laser is ‘digested’ in the material according various scenarii that we will discuss in the sequel.

Three cases that represent the majority of scenarii in laser manufacturing will be considered in this lecture.

Before analyzing them one-by-one, let us first go through some basics about optical waves and linear absorption mechanism.

Essence of laser micromachining?

- Too players: *Light* and *Matter*

⇒ some basics in optics

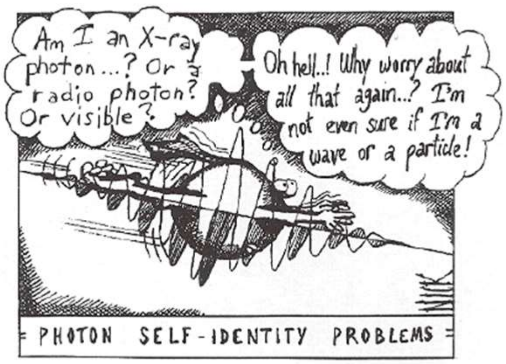
⇒ some primer about the structure of matter and how light interacts with it

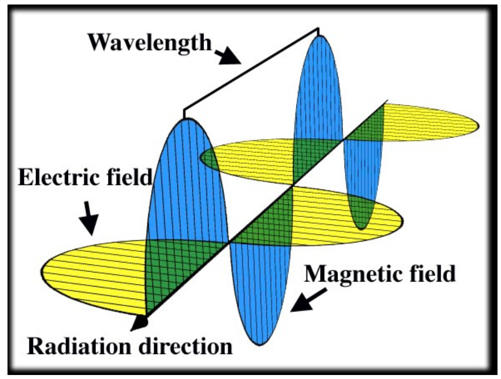
Laser-matter interaction is multidisciplinary discipline that includes optics and materials science.

Here we will focus on some basic aspects of optics and linear absorption mechanism in materials and how the absorbed energy is 'digested' by the material.

Light is…

- An Electro-Magnetic wave…
- A particle





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From optics lectures, we know that light can be seen either as an electromagnetic wave (the 'electromagnetism' description) or as a particle and a wave, in the quantum description (the duality particle-wave description).

The photons… (the 'light' particles)

- Mass less…
- No charge
- Energy

$$E = \hbar\omega = h\frac{c}{\lambda}$$

$$\hbar = \frac{h}{2\pi}$$

Pulsation

Propagation speed

Planck constants

Wavelength

The shortest the wavelength, the highest the photon energy!

In the quantum mechanics description, the light particle transporting energy are called photons. These particles have no mass and no charge but carries energy.

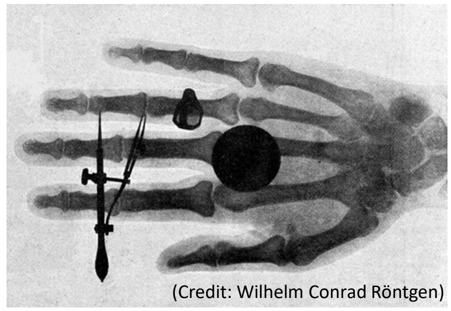
The quantized amount of energy carried by a photon is proportional to the angular frequency, and therefore, to the ratio of the propagation speed in the medium and the wavelength of the light beam.

The proportionality constant is the Planck constant: h = 6.62607015×10^{-34} J·s.

As a direct consequence, light wave of shorter wavelength have more energetic photons than light of longer wavelength, since the photon energy is inversely proportional to the wavelength.

CLASS: γ, HX, SX, EUV, NUV, NIR, MIR, FIR, EHF, SHF, UHF, VHF, HF, MF, LF, VLF, VF/ULF, SLF, ELF

FREQUENCY	WAVELENGTH	ENERGY
300 EHz	1 pm	1.24 MeV
30 EHz	10 pm	124 keV
3 EHz	100 pm	12.4 keV
300 PHz	1 nm	1.24 keV
30 PHz	10 nm	124 eV
3 PHz	100 nm	12.4 eV
300 THz	1 µm	1.24 eV
30 THz	10 µm	124 meV
3 THz	100 µm	12.4 meV
300 GHz	1 mm	1.24 meV
30 GHz	1 cm	124 µeV
3 GHz	1 dm	12.4 µeV
300 MHz	1 m	1.24 µeV
30 MHz	10 m	124 neV
3 MHz	100 m	12.4 neV
300 kHz	1 km	1.24 neV
30 kHz	10 km	124 peV
3 kHz	100 km	12.4 peV
300 Hz	1 Mm	1.24 peV
30 Hz	10 Mm	124 feV
3 Hz	100 Mm	12.4 feV


(Credit: Wilhelm Conrad Röntgen)

Rotational energies of molecules	10^{-5} eV
Vibrational energies of molecules	0.1 eV
Energy between outer electron shells in atoms	1 eV
Binding energy of a weakly bound molecule	1 eV
Energy of red light	2 eV
Binding energy of a tightly bound molecule	10 eV
Energy to ionize atom or molecule	10 to 1000 eV

($1eV = 1.602176634\times10^{-19}$ J)

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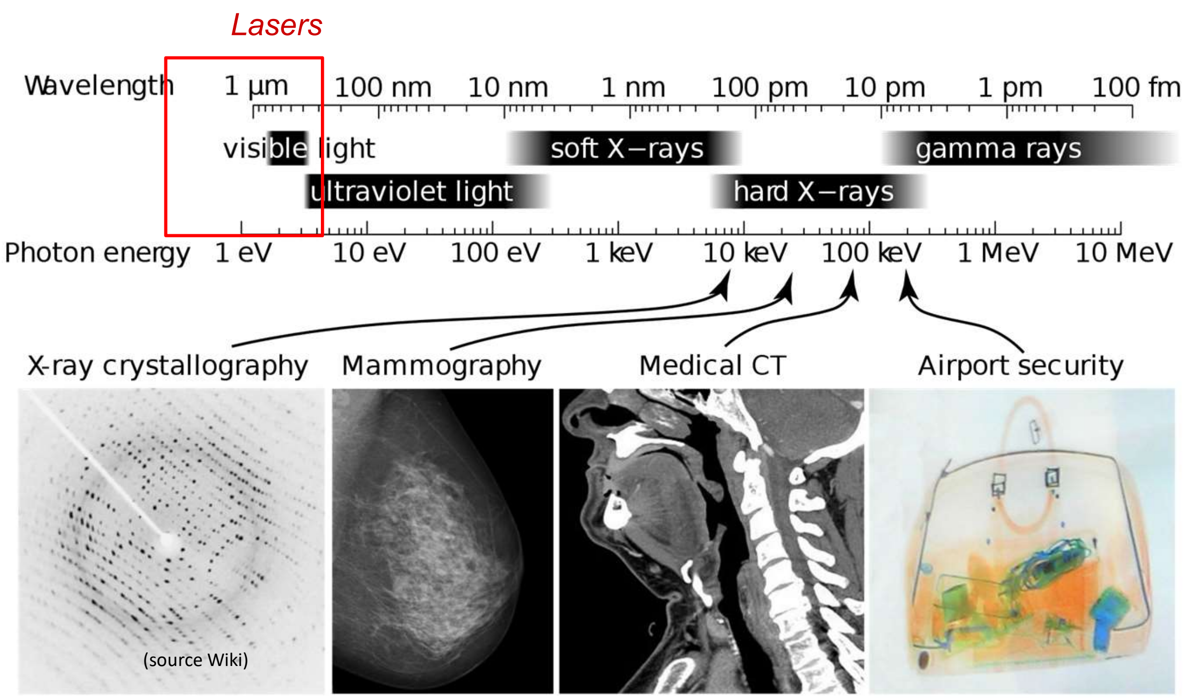
This slides compares the energy carried at various frequencies.

In the optical-visible range, the photon energy are typically 1eV.

This is interesting to compare this value with typical energy-range at the atomic scale, such as rotational energies in molecule, ionization, etc.

1eV is typically the range of energy for electrons bound to atoms.



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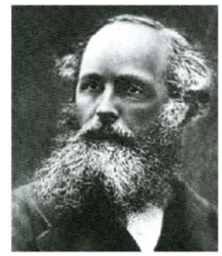
Another way of comparing frequencies with their corresponding applications.

Maxwell equations

Electric field : Gauss' law

1) $\vec{\nabla}\cdot\vec{E}=\rho/\varepsilon_0$ (in the presence of stationary charges)

$\vec{\nabla}\cdot\vec{E}=0$ (in vacuum)



James Clerk Maxwell
(1831-1879)

Magnetic field

2) $\vec{\nabla}\cdot\vec{B}=0$

3) Faraday's law: $\vec{\nabla}\times\vec{E}=-\dfrac{\partial\vec{B}}{\partial t}$

4) Ampère's law: $\vec{\nabla}\times\vec{B}=\mu_0\varepsilon_0\dfrac{\partial\vec{E}}{\partial t}$

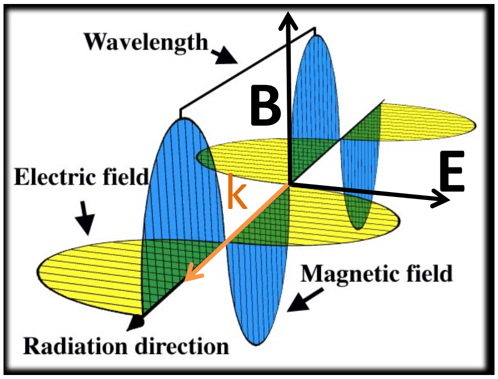
$$\vec{\nabla}^2\vec{E}-\mu_0\varepsilon_0\frac{\partial^2\vec{E}}{\partial t^2}=0$$

$$\vec{\nabla}\times\left(\vec{\nabla}\times\vec{E}\right)=\vec{\nabla}\left(\vec{\nabla}\cdot\vec{E}\right)-\vec{\nabla}^2\vec{E}$$

In the electromagnetic (EM) description, the behavior of a light wave is described using the four equations of Maxwell that encapsulates all electromagnetic theory.

Combining these four equations in the case of vacuum (i.e. no charge present), we can express them in the form of two partial differential equations, expressed separately in term of electrostatic or magnetic field.

In what follows, we focus only on the equation that described the electrostatic field behavior in vacuum.



3D wave equation for a light-wave electric field

$$\vec{\nabla}^2 \vec{E} - \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\boxed{\vec{E}(x,y,z,t) = \Re\left\{ \underset{\sim}{\vec{E}_0} \exp[i(\vec{k}\cdot\vec{r} - \omega t)]\right\}}$$

$$\vec{r} \equiv (x,y,z) \qquad \vec{k} \equiv (k_x, k_y, k_z)$$

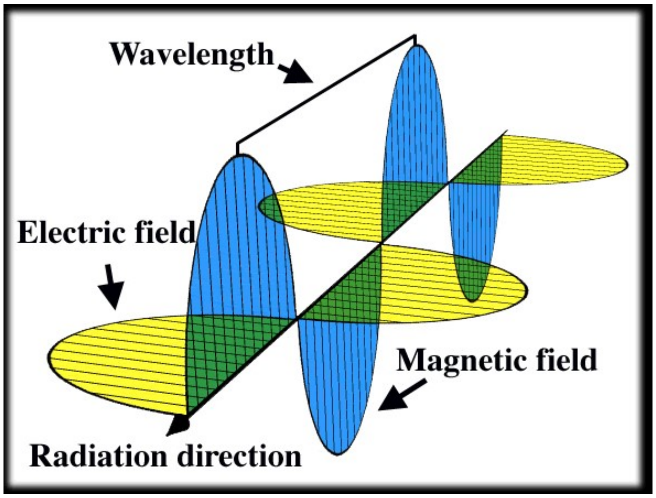
$$\vec{k}\cdot\vec{r} \equiv k_x\, x + k_y\, y + k_z\, z$$

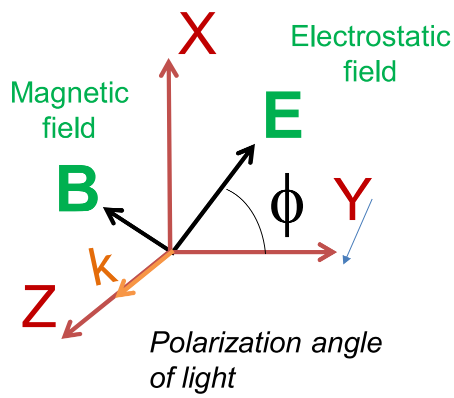
(Note: This is one of the solution but not the only one… Ex. Bessel)

One solution of the partial derivative equation (PDE) is an electrostatic field with an exponential component carrying a propagating component and a time varying one.

The k vector describes the direction of propagation.

Polarization of a light-wave





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The vectors (**k, E, B**) form a triad, perpendicular, one to another. **E** and **B** vectors are in a plane perpendicular to the direction of propagation.

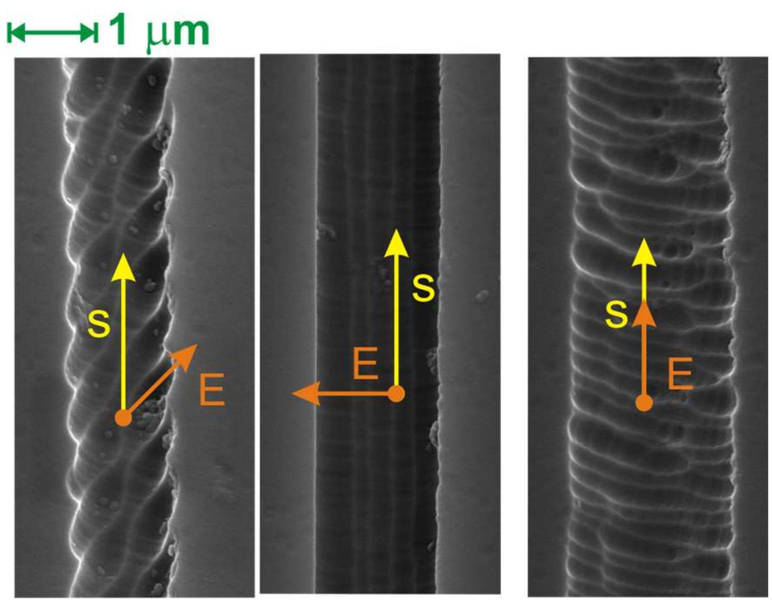
The electrostatic vector is the most important to consider in our case as it interacts with the electrons in the matter.

One important parameter is the **polarization of light**. It is defined by the orientation of the **E** vector with respect to a *fixed* coordinate frame (X, Y, Z) as illustrated above.

Various polarization states exist. A linear polarization state means that the E vector does not move with a fixed reference frame and keep the same direction.

In other polarization state, the E vector moves in time in a fixed coordinate frame, as the EM wave propagates.

Example how the polarization may affect a micro-machining morphology



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The polarization state can have a strong influence on the laser-matter interaction.

The illustration above shows some micromachining done in a glass (fused silica). In this process, the laser is used to modify the material such that when it is etched after in an acid bath (HF), the exposed regions with the laser are dissolved faster than the rest of the material.

In the example above, the same beam parameters are used in term of energy and energy deposited in the material. Lines are written along the surface. A top view of the material morphology after etching is shown.

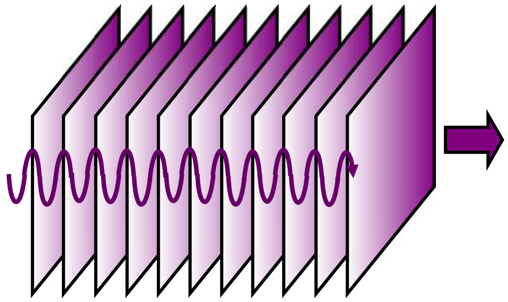
The only parameter that was changed is the polarization state of the beam, and here, how the electrostatic field is oriented with respect to the laser writing direction, denoted here with a **s** vector. Three examples are shown. In the left case, the E field is oriented at 45 deg from the writing direction s. In the middle, the E field is oriented perpendicular to the writing direction and finally, on the far right, it is oriented parallel to the writing direction.

The different of morphologies are evident, illustrating the importance of the polarization of the laser beam on the process.

It is often the case that in laser manufacturing, the polarization has a strong influence on the end-result.

$\underset{\sim}{E}_0 \exp[i(kx - \omega t)]$ is called a **plane wave.**

A plane wave's contours of maximum field, called wavefronts or phase-fronts, are planes. They extend over all space.



A wave front propagates at the speed of light.

- A plane wave's wavefronts are equally spaced, a wavelength apart.
- They're perpendicular to the propagation direction.

(credit illustration / Rick Trebino)

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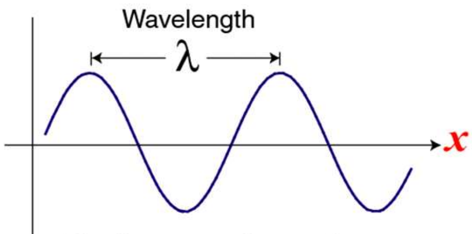
This solution describes a planar wave that propagates in space. The contour of maximum field in the wave are called wavefronts (or sometimes, phase-fronts).

The distance between two wavefronts is the wavelength. Wavefronts are perpendicular to the direction of propagation.

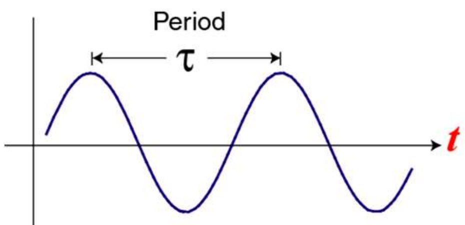
Characteristics of a wave

Spatial

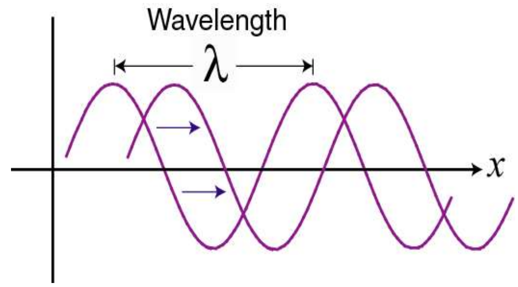


The k-vector: $k = 2\pi/\lambda$
The wave number: $\kappa = 1/\lambda$

Temporal



The angular frequency: $\omega = 2\pi/\tau$
The frequency: $\nu = 1/\tau$



Propagation velocity

$$V = \frac{\lambda}{\tau} = \left(\frac{2\pi}{\tau}\right)\left(\frac{\lambda}{2\pi}\right) = \frac{\omega}{k}$$

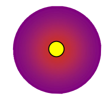
Propagating waves are defined with the two key parameters. The wavelength that defines the spatial periodicity. The amplitude of the k vector is itself defines as $2\pi/\lambda$.

A propagating optical wave oscillates both in time and space. One can define a propagation velocity V, that defines how fast is the wave propagating. This quantity is the ratio between pulsation and k vector.

Motion in atoms and molecules: 'Everything vibrates!'

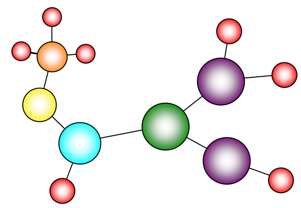
- Electrons vibrate in their motion around nuclei

High frequency
~10^{14} - 10^{17} cycles per second.



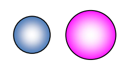
- Nuclei in molecules vibrate with respect to each other

Intermediate frequency:
~10^{11} - 10^{13} cycles per second.



- Nuclei in molecules rotate

Low frequency
~10^{9} - 10^{10} cycles per second.



(adapted from R. Trebino, Georgia Tech.) 32

Let us now discuss how an EM wave may interact with matter.

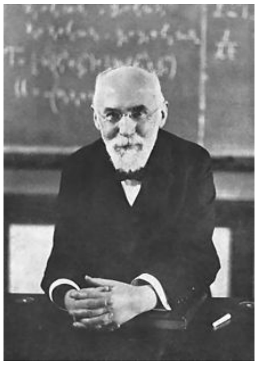
The first observation is that everything oscillates within atoms and molecules.

- Electrons constantly vibrate around the nuclei of an atom.
- Nuclei in molecules moves one with respect to another.
- Finally, nuclei in molecules may also rotate.

These vibrations have different time scale.

We have now to consider what happens when an EM wave comes into interaction with charges that are vibrating.

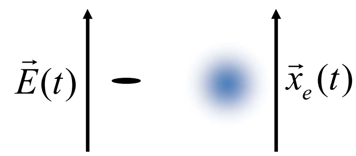
One approach is to describe these vibrations modes as many oscillators in motion, responding to a force excitation resulting from the EM wave that propagates through the matter.



Hendrik Antoon Lorentz
(1858-1928)

How to model the material response to an incoming EM wave? (Lorentz dispersion model)

- In a first approximation, it can be modelled by an oscillator



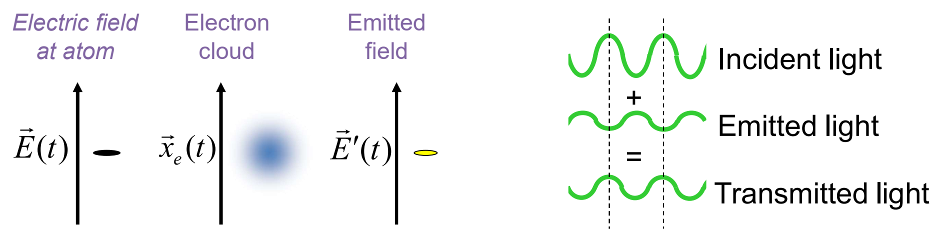
Having made these comments about quantum mechanics descriptions, let us go back to the more classical approach.

In what follows, we consider the Lorentz dispersion model to describe how light will interact with matter. This model was proposed by the Dutch scientist, Hendrik Lorentz.

The basic idea is to consider the vibration of the electron cloud around the atom as a classical harmonic oscillator that is forced by the incoming oscillating electrostatic field provided by the laser beam.

Light excites atoms, which emit light that adds (or subtracts) with the input light...

When light of frequency ω excites an atom with resonant frequency ω_0:



An excited atom vibrates at the frequency of the light that excited it and re-emits the energy as light of that frequency.

Our problem (illustrated above) can be defined as follows:

- An atom is put in an oscillating field provided by the incoming light beam.
- The electron cloud of the atoms also vibrates and is further excited by the incoming electrostatic field.

In this model, the excited atom reemits light at the same frequency than the excitation, but at a different amplitude.

The Damped Forced Oscillator

Interaction between light and electrons can be modeled by an harmonic oscillator experiencing a sinusoidal force and viscous damping term.

$$m_e \frac{d^2 x_e}{dt^2} + m_e \gamma \frac{dx_e}{dt} + m_e \omega_0^2 x_e = -eE_0 \exp(-i\omega t)$$

Excitation field (light): $E_0 \exp(-i\omega t)$; Excitation pulsation: ω

$$x_e(t) = \left[\frac{(e/m_e)}{(\omega_0^2 - \omega^2 - i\omega\gamma)} \right] E(t)$$

- Position of the Electron as a function of time: $x_e(t)$
- Electron charge: e
- Electron mass: m_e
- Resonant pulsation: ω_0
- Damping coefficient: γ
- Excitation field: $E(t)$

The electron oscillates at a finite an amplitude at the light frequency and with a potential phase shift.

Under these assumptions, the electron cloud motion (x_e) can be seen as a classical damped harmonic oscillator, much like a spring with a mass attached to it, the mass being the mass of an electron.

One particular solution of this equation is:

$$x_e(t) = \left[\frac{(e/m_e)}{(\omega_0^2 - \omega^2 - i\omega\gamma)} \right] E(t)$$

In which the various parameters are described above, and E(t) is the excitation field, i.e., the incoming propagating light.

Damped forced oscillator solution for light-driven atoms

- Sinusoidal response with a frequency-dependent strength

$$x_e(t) \propto -\left[\frac{1}{(\omega_0 - \omega - i\gamma/2)}\right] E(t)$$

- **$w << w_0$** : the electron vibrates in phase with the light wave

$$x_e(t) \propto \left[\frac{1}{(\omega_0)}\right] E(t) \propto E(t)$$

- **$w = w_0$** : the electron vibrates $-\pi/2$ out of phase with the light wave

$$x_e(t) \propto \left[\frac{1}{(-i\gamma/2)}\right] E(t) \propto iE(t)$$

- **$w >> w_0$** : the electron vibrates π out of phase with the light wave:

$$x_e(t) \propto \left[\frac{1}{(-\omega)}\right] E(t) \propto -E(t)$$

Let us further simplify the solution of the equation and consider the most relevant component.

When the excitation vibration w is much smaller than w_0, the electron vibrates in phase with the light wave.

When we are the resonance, the electron vibrates out of phase by $\pi/2$. The width of the vibration peak is governed by the damping coefficient.

Finally, when w is much larger than w_0, the vibration is out of phase by π from the light wave.

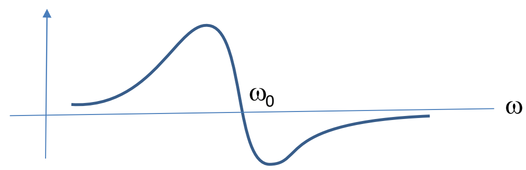
In expression above, the first term describes a complex Lorentzian function.

The Complex Lorentzian function

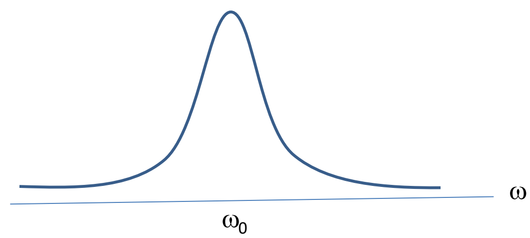
$$\frac{1}{\delta - i\Gamma} = \frac{1}{\delta - i\Gamma}\left(\frac{\delta + i\Gamma}{\delta + i\Gamma}\right) = \left(\frac{\delta}{\delta^2 - \Gamma^2}\right) + i\left(\frac{\Gamma}{\delta^2 - \Gamma^2}\right)$$

Real part　　Imaginary part

$$\left[\frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 - \left(\frac{\gamma}{2}\right)^2}\right]$$



$$\left[\frac{\frac{\gamma}{2}}{(\omega_0 - \omega)^2 - \left(\frac{\gamma}{2}\right)^2}\right]$$



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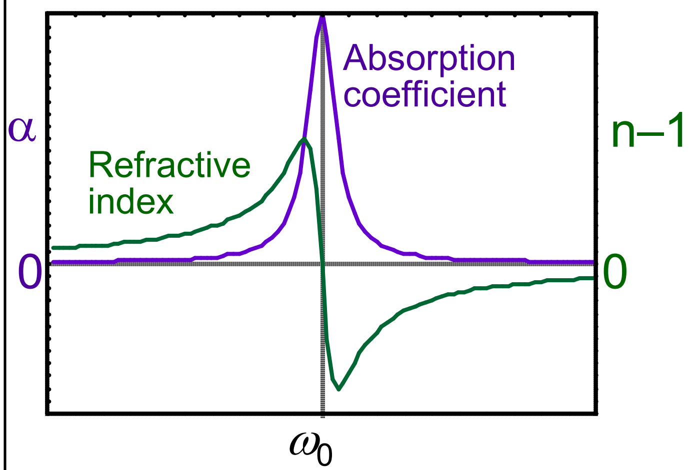
The complex Lorentz function, can be decomposed into a real and an imaginary part as shown above.

Refractive index and Absorption coefficient



Describe the absorption coefficient (imaginary part) of the Lorentz function

$$\alpha = \left(\frac{Ne^2}{2\varepsilon_0 c_0 m_e}\right)\frac{\gamma/2}{(\omega_0-\omega)^2+(\gamma/2)^2}$$

$$n-1 = \left(\frac{Ne^2}{4\varepsilon_0 m_e}\right)\frac{1}{\omega}\frac{\omega_0-\omega}{(\omega_0-\omega)^2+(\gamma/2)^2}$$

$$\omega = \frac{c}{\lambda}$$

The imaginary part describes the absorptivity of the material. The full expression using this model is:

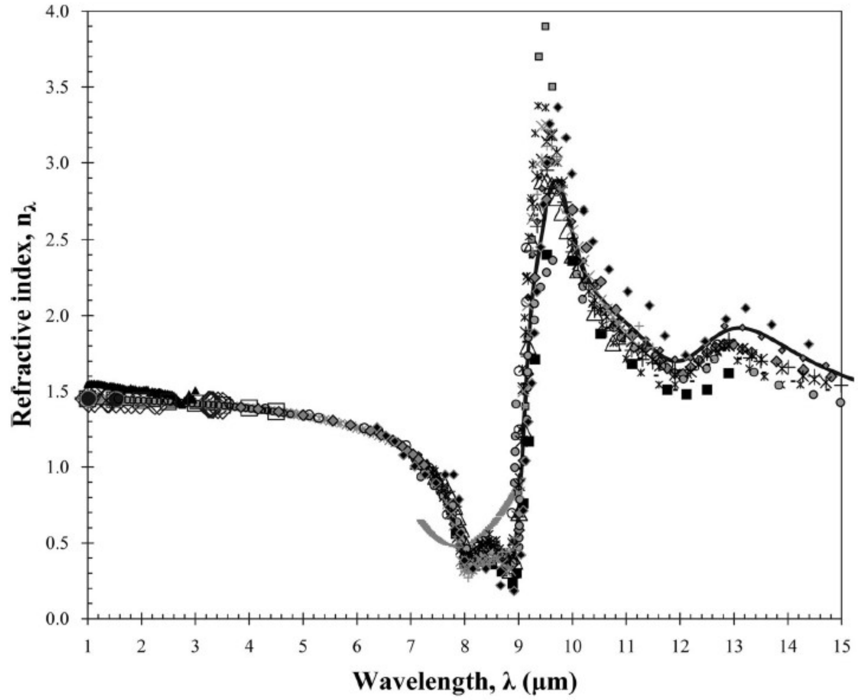
$$\alpha = \left(\frac{Ne^2}{2\varepsilon_0 c_0 m_e}\right)\frac{\gamma/2}{(\omega_0-\omega)^2+(\gamma/2)^2}$$

It peaks at the resonant frequency w_0 for the atom.

The real part is the propagative part and is described a property in materials, known as the refractive index.

$$n-1 = \left(\frac{Ne^2}{4\varepsilon_0 \omega m_e}\right)\frac{\omega_0-\omega}{(\omega_0-\omega)^2+(\gamma/2)^2}$$

Example: Fused silica (glass)



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As an illustration, the curve above describes the measured refractive index as a function of the wavelength for fused silica (a glass) as a function of the wavelength.

The electromagnetic wave in a medium

$$k \rightarrow nk \quad \text{and} \quad \lambda \rightarrow \lambda / n$$

$$E(z,t) = E_0(0)\exp[(-\alpha/2)z]\;\exp[i(nkz - \omega t)]$$

Absorption attenuates the field

Refractive index (Change the propagation velocity)

At a depth (z):

$$|E_0(z)| = |E_0(0)|\exp[(-\alpha/2)z]$$

The two expressions before give us a means to describe how an EM wave will propagate in a material.

The first part contains the attenuation of the EM wave as it penetrates inside the material. It is an exponential decay along the propagation axis that describes the progressive absorption of the incoming light beam.

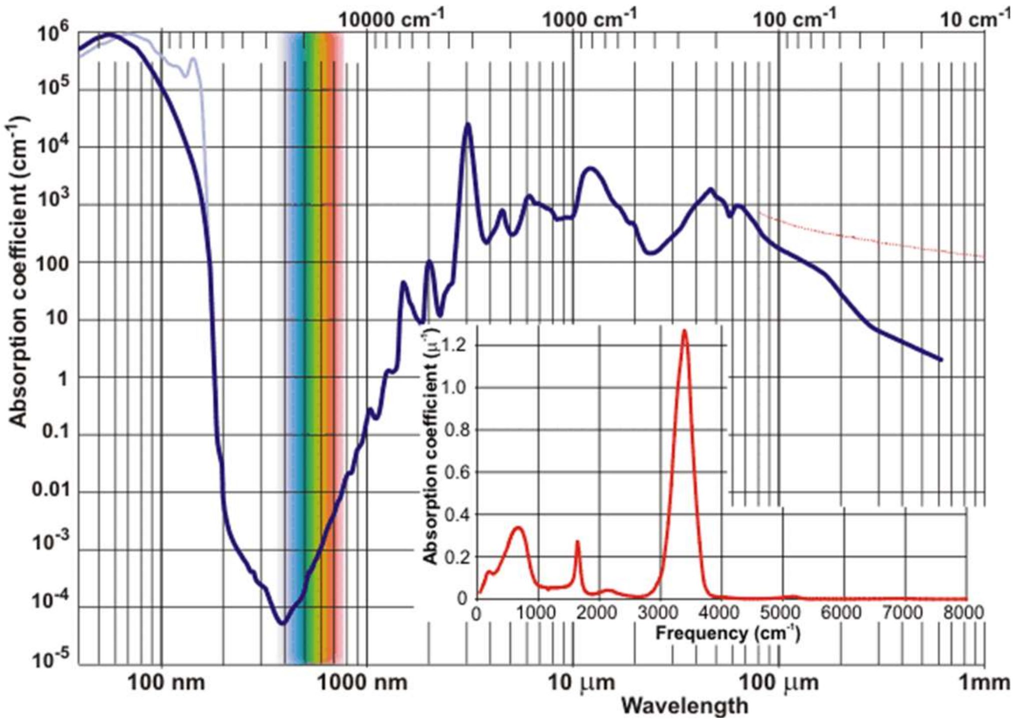
The second part of the expression is the propagating element, which like before describes how the wave propagates further in the material.

Note that k vector is multiply by the refractive index and therefore the wavelength gets divided by the refractive index.

Recalling the expression of the velocity of the propagating wave. It means that the wave 'slow' down as it penetrates inside the material.

$$V = \frac{\lambda}{\tau} = \left(\frac{2\pi}{\tau}\right)\left(\frac{\lambda}{2\pi}\right) = \frac{\omega}{k}$$

Illustration 1: absorption spectra of the Ocean



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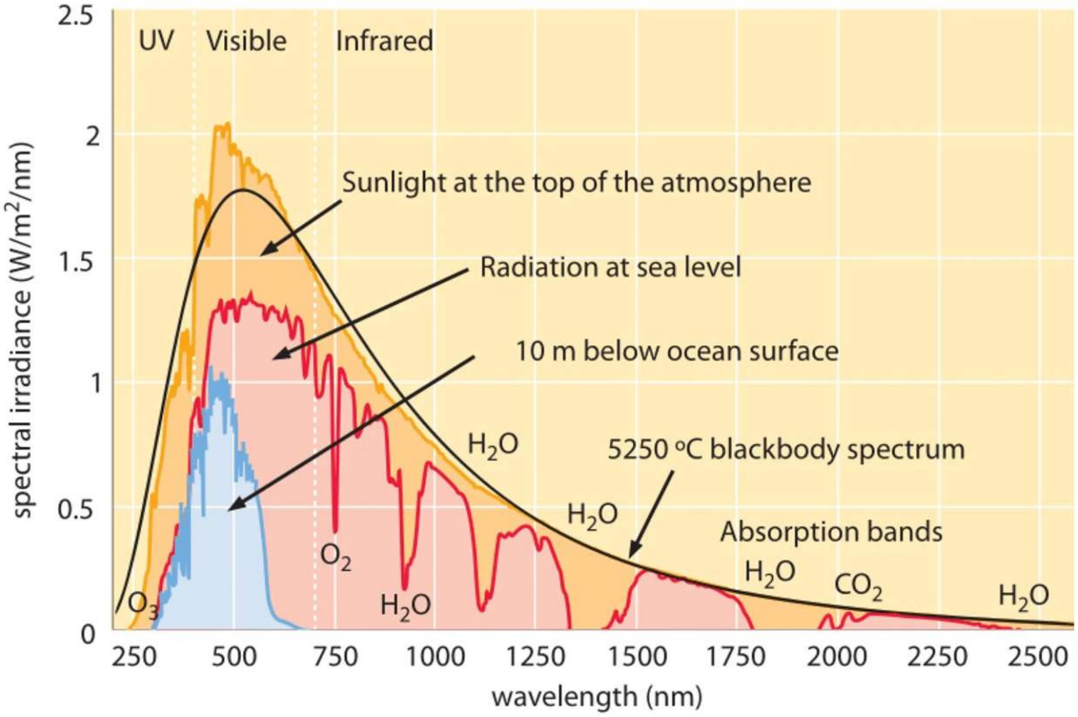
The example above shows a typical absorption spectrum of water. As can be seen, the wavelength that is absorbed the least is the blue color.

Illustration 2:
Solar light from the sky to the ground and the sea



(source OceanOptics)

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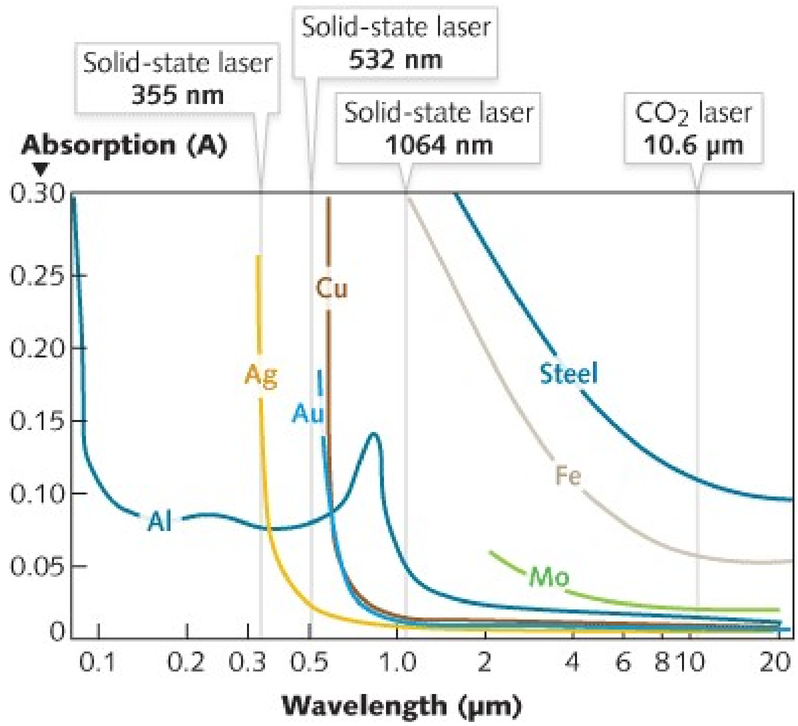
Another illustration about absorption of light.

The graph shows in black the theoretical blackbody spectrum (black lines). The spectral emission of the sun light (dark yellow) that can be modeled as a black body, the light as seen at the sea level (in red), 10 meter below ocean surface (in blue).

Part of the emitted light from the sun gets absorbed at specific wavelength when it crosses the atmosphere, which can be explained by the interaction of specific molecules. These peaks correspond to resonances with vibration at the molecular level as described with the Lorentz model. Hence, observing the spectrum of sun light after crossing the atmosphere can tell us about the molecule that are actually present.

Further under water, 10-meter deep, only a small portion of the visible spectrum remains as the majority of the IR spectrum is absorbed, and only a small portion of the spectrum emitted by the sun light remains.

Illustration 3:
Manufacturing / Absorption of some metals...



(source Trumpf)

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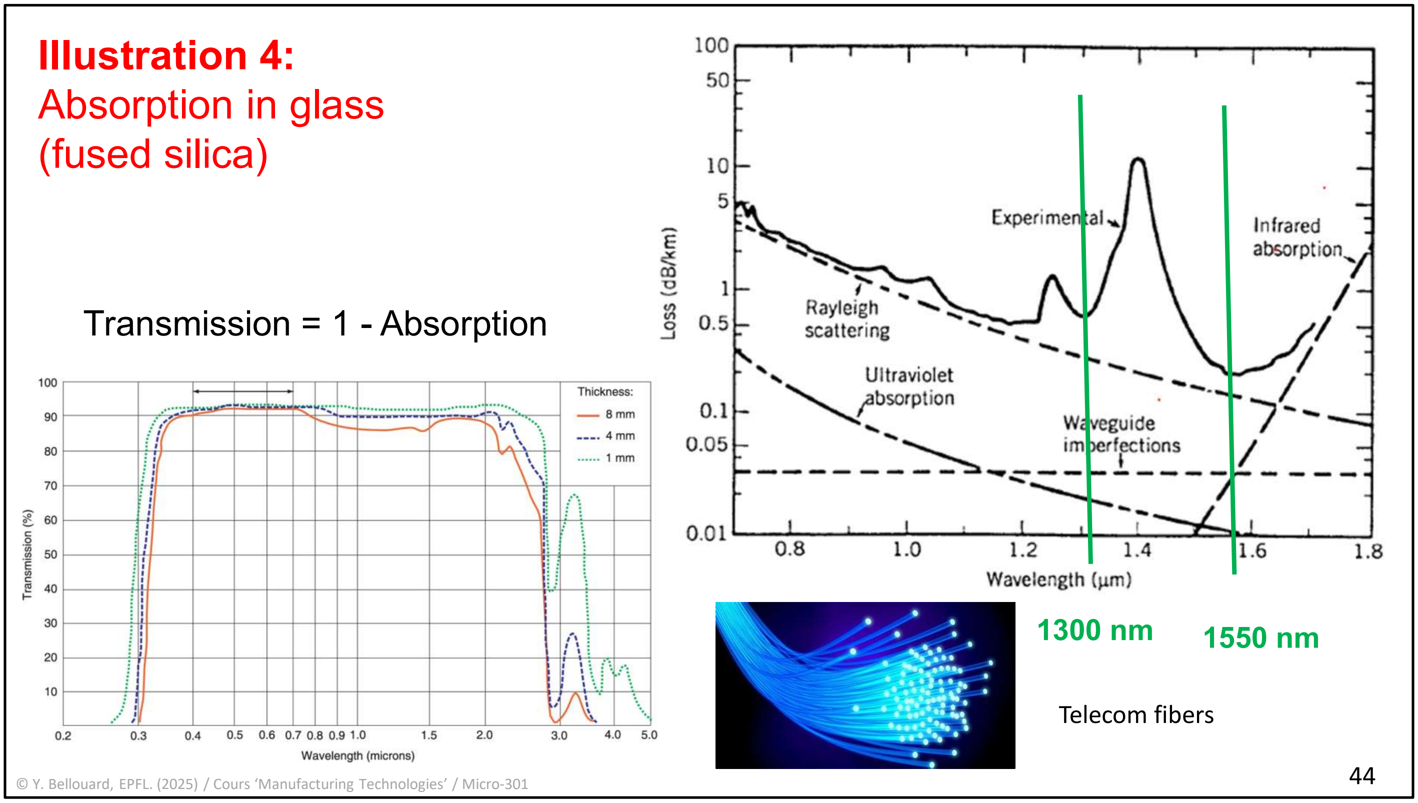
Another example, more related to manufacturing, this time about common metals.

Above are indicated typical wavelengths of industrial/commercial lasers used in manufacturing.

Let us consider for instance the case of silver. As one can see, it absorbs nearly nothing above 500 nm is highly reflective. Therefore, it would be particularly difficult to machine as only a very small amount of the incoming energy would be absorbed.

Note that not absorbing, does not mean that the material is transparent. Silver does reflect very well without absorbing.

In this illustration to more efficiently get light energy absorbed in the material, when would have to consider a laser emitting at 355 nm.



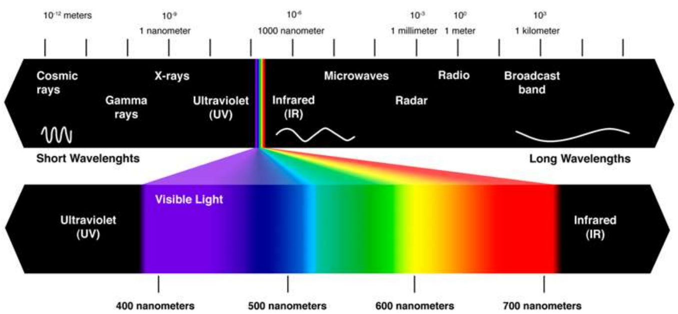
A last example, related to the fiber telecommunications. In the telecom business, the usual wavelength used is at 1550 nm.

The reason for this choice of wavelength is related to the most efficient wavelength to transport in optical fibers. In telecommunications, bits of information are transported as optical signals that needs to be propagated over long distances, i.e., eventually tens to kms of fibers.

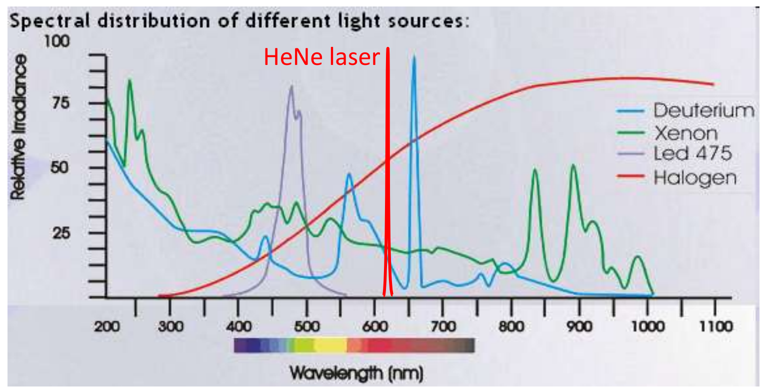
As seen in the introductory lectures, optical fibers are made of silica glass. Like any materials, the material absorbs certain wavelengths. As a glass is it transparent to certain wavelengths. However, even transparent, there is always a little amount of light absorbed, for instance due to impurities, defects, and other imperfections.

Looking at the losses for given spectral information, silica has a minimum of absorption at 1550 nm, which explains why it was the wavelength selected or transporting optical bits of information. It corresponds to the wavelength where there is the least amount of interaction with the material.

Emission spectra of a light source



(source: http://www.theskepticsguide.org/)



	Largeur spectrale
• Xenon / Halogen	> 1 µm
• LED	~ 100-150 nm
• Un laser est quasi-monochromatique!	< 10 nm

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Light sources can have very different emission spectra. A few examples are illustrated above. For instance Xenon lamps have a broad emission spectral range, but quite inhomogeneous.

A LED has a shorter range of 150 nm that can be centered on various wavelength depending of its color.

Among all the sources, lasers are characterized by the fact that their emission spectrum is almost monochromatic, which in other words means that they emit a single wavelength.

For instance, a He-Ne laser (red laser) will emit light around 632 nm.

Mean Photons flux density for various sources

One photon of visible light = 10^{-19} Joules
F is the **photon flux**, or the number of photons/sec in a beam.

Light Source	Mean Photon Flux Density Φ/A in units of (photons/$s \cdot m^2$)
Laserbeam (10 mW, He-Ne, focused to 20 μm)	10^{26}
Laserbeam (1 mW, He-Ne)	10^{21}
Bright sunlight	10^{18}
Indoor light level	10^{16}
Twilight	10^{14}
Moonlight	10^{12}
Starlight	10^{10}

Source Siegman, 'Lasers'

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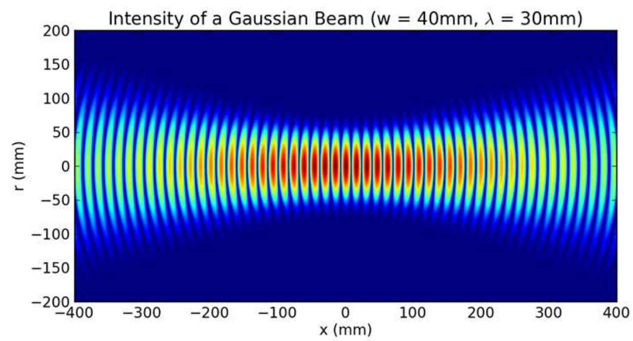
Another interest aspect is to compare light sources in terms of density of photons emitted through a meter square per second.

As can be seen, even for a simple laser beam of 1 mW (typically a laser-pointer), there is a thousand-time more photons emitted than in the case bright sunlight and hundred of thousand-time more than indoor light.

A comparison typical laser for manufacturing can emits from hundreds of mW to kW of power!

Laser important characteristics

- ✓ **Monochromatic** (= one wavelength)
- ✓ **Coherent** source (spatial/temporal)
- ✓ Emits **Gaussian beams** (i.e. Intensity follows a Gaussian distribution)
- ✓ High **density** of photons > High density of energy



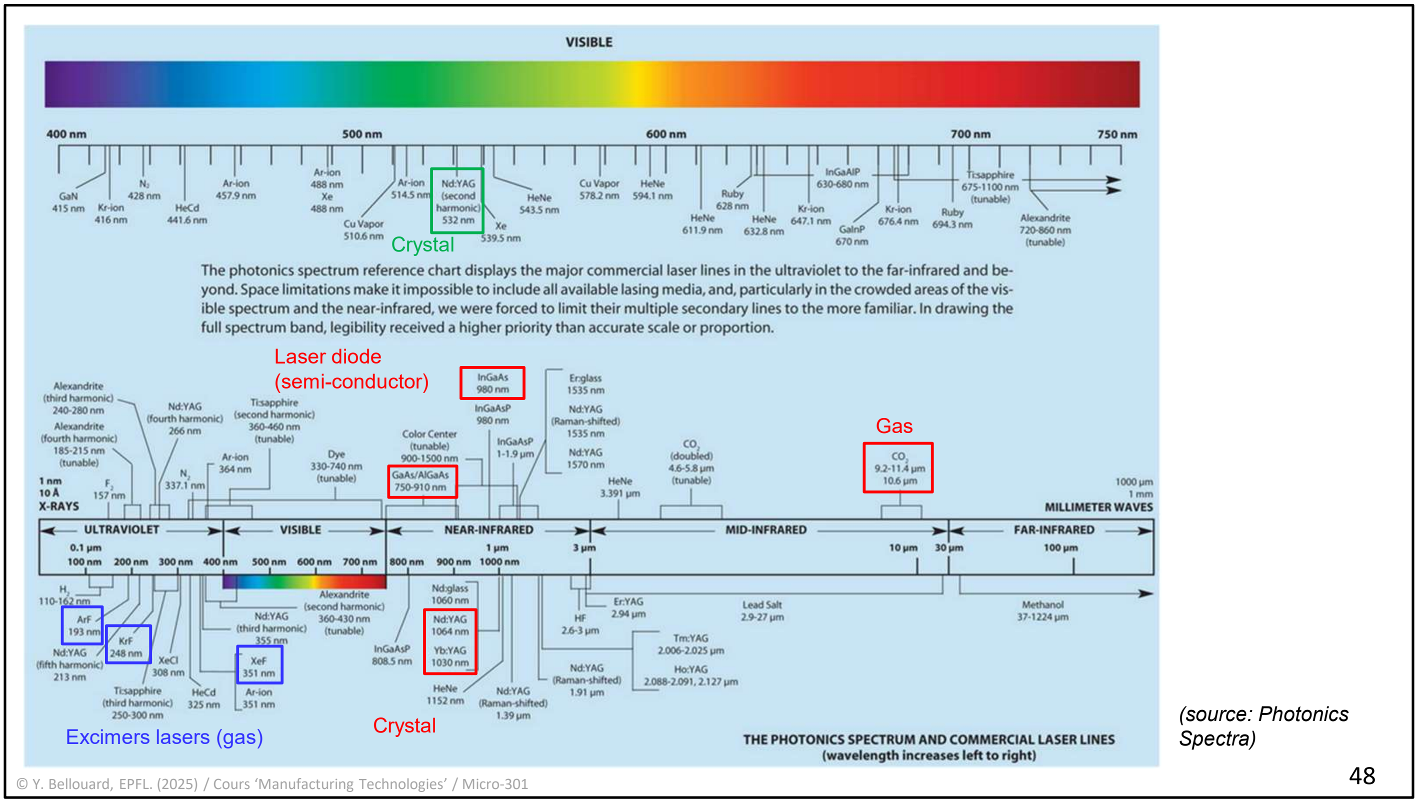
The important characteristics of a laser are listed above.

The coherence relates to two aspects, the coherence time and coherence length. It is a metrics on how much a sinusoid stays consistent without phase jump over time or propagation length.

For instance if we would be able to observe the oscillation at the laser wavelength while it propagates, the coherence length would mean how long would the sinusoidal oscillations would be, before it becomes disrupted and a jump of phase occur. This property is particularly interesting in metrology, a bit less for manufacturing.

As discussed before, lasers are characterized by a very high density of photons emitted per meter-square.

Finally, lasers emit Gaussian means. It means that the profile of intensity across of laser beam is governed by a Gaussian function.

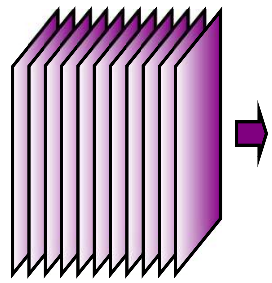


This chart shows the vast number and types of lasers that exist at various wavelength. In this fauna, the most common lasers used in manufacturing are divided into four main categories.

- The Excimer lasers characterized by short wavelengths (in the UV)
- The 'green laser' emitting around 515 nm
- The short-IR lasers emitting around 1030-1064 nm.
- … and mid-IR lasers emitting around 10 microns.

Beams (*localized* waves in space)

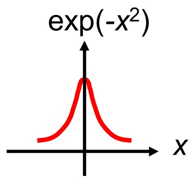
A plane wave has flat wave-fronts throughout all space. It also has infinite energy… Does not exist!

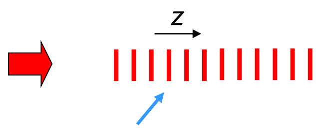


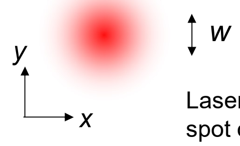
Real waves are *localized spatially*.

Example of a localized wave: A Gaussian beam

$$\underset{\sim}{E}(x,y,z,t) = \underset{\sim}{E}_0 \exp\left[-\frac{x^2+y^2}{w^2}\right]\exp[i(kz-\omega t)]$$







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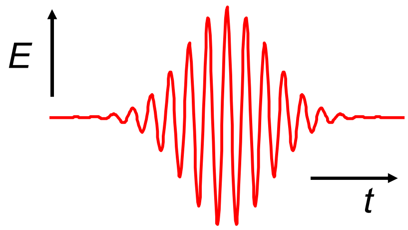
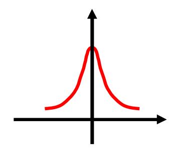
From Maxwell equations, we found that a theoretical solution of the propagation equation is a planar wave. Such a wave is not physically possible as it would have an infinite energy.

Real waves are localized spatially.

For a laser beam, the electrical field will be modulated by a Gaussian function as shown above. This is what gives the hazy contour of a laser beam spot.

Pulses (localized waves in time)



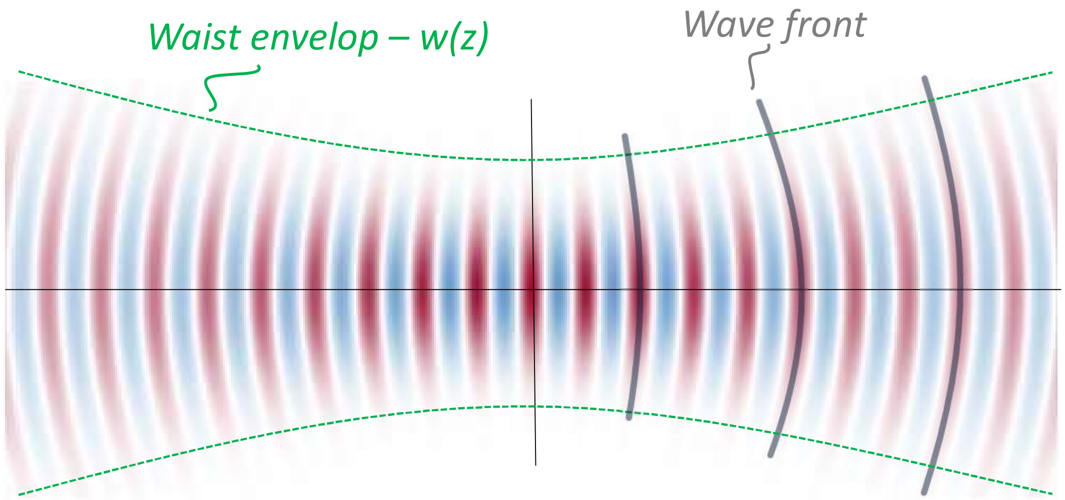


$$\underset{\sim}{E}(x,y,z,t) = \underset{\sim}{E}_0 \exp\left[-\frac{t^2}{\tau^2}\right] \exp\left[-\frac{x^2+y^2}{w^2}\right] \exp[i(kz-\omega t)]$$

This is the equation for a laser pulse.

Often lasers are emitting pulses. In such case, the equation of the propagating field is modified to add a time-dependent amplitude.

Propagating Gaussian beam (electrostatic field distribution)



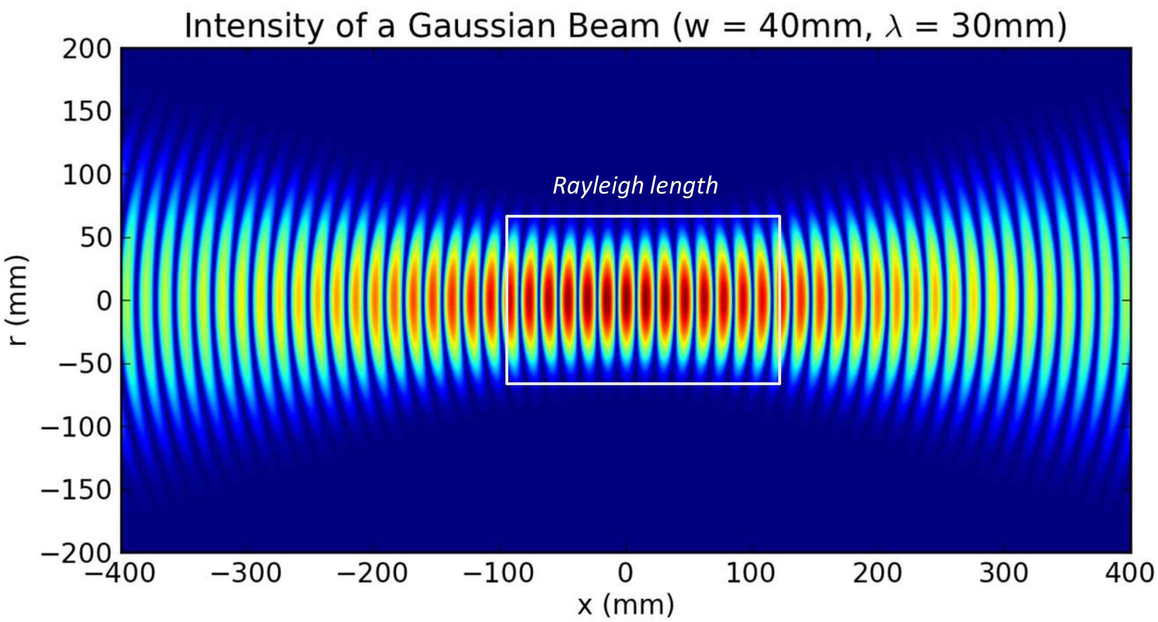
(adapté de RP Photonics)

When focused, a Gaussian beam propagates along a curve called 'waist'.

The representation above illustrates with colors, the oscillation of the electrical field while propagating.

The wavefront is the curve that describes the shape of the electrical field intensity distribution of equal intensity. At the focus (i.e., in the center of the figure above), the wavefront is flat.

Notice that there is no strict boundaries on the wavefront on the edges. This is due to the Gaussian nature of the electrical field intensity.

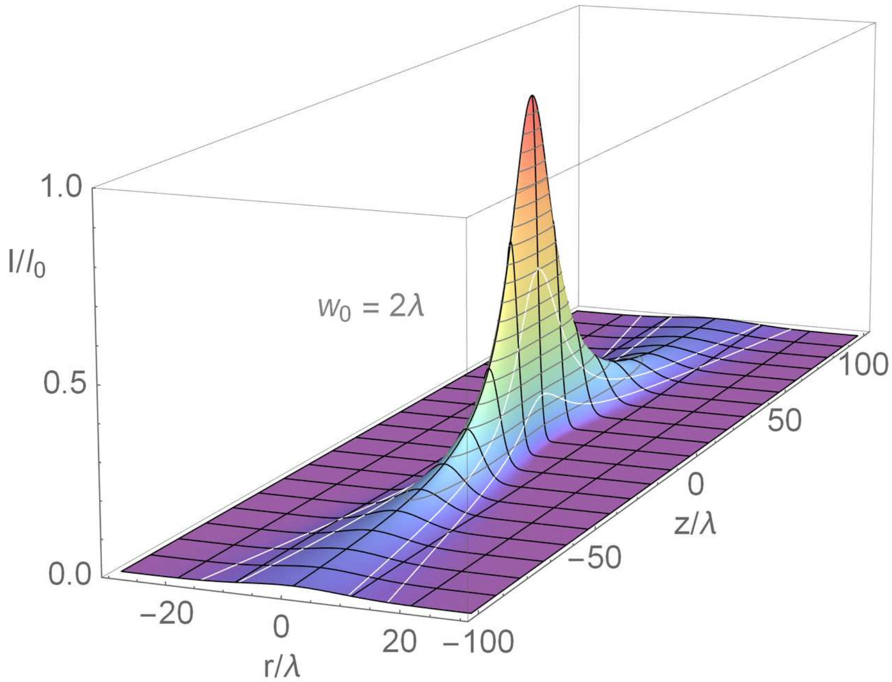


(illustration Wikipedia)

Another representation of the same thing (with arbitrary units).

The electrical field intensity is the same on along a wavefront. Hence as the wavefront get more spatially confined, culminating at the focal spot, the peak intensity gets higher.

3D view



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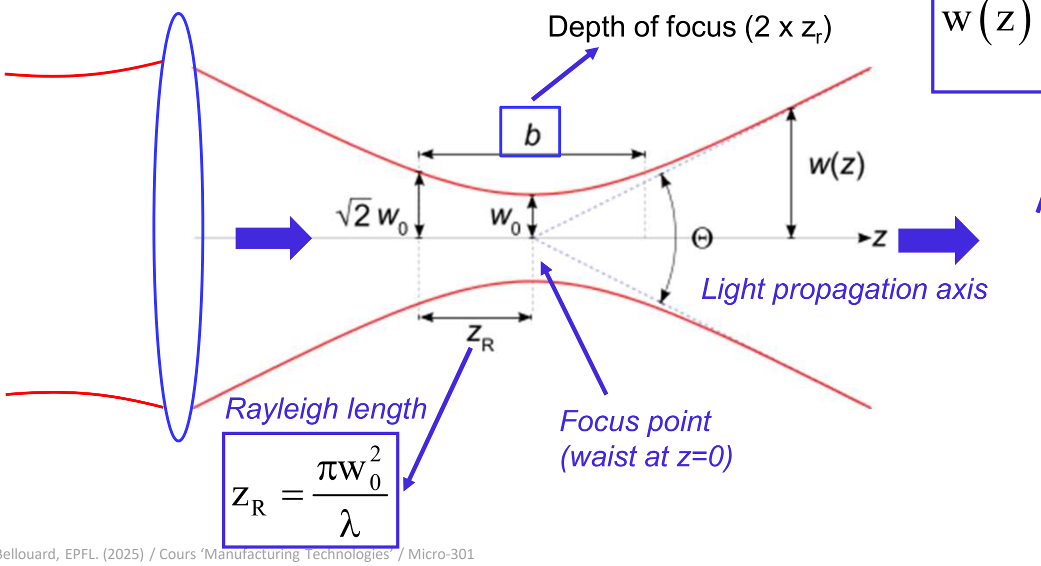
A dimension-less representation of a beam being focused at a position 0. As it reaches the focal point, the beam intensity per unit surface becomes the highest.

Important definitions of a Gaussian beams

- Beam waist w(z) / 'Spot size'
- Rayleigh length (z_r)

Beam waist at a position z

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$



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The beam waist equation at a position z is mathematically described by the equation above.

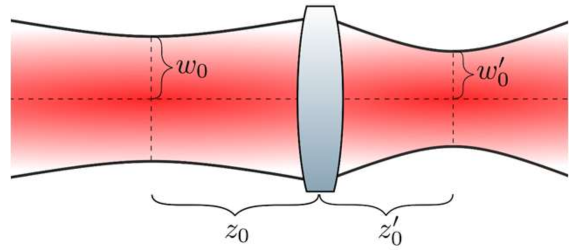
Let us imagine a laser beam being focused by a lens (shown here as a blue ellipse). The waist is the smallest at the focal point.

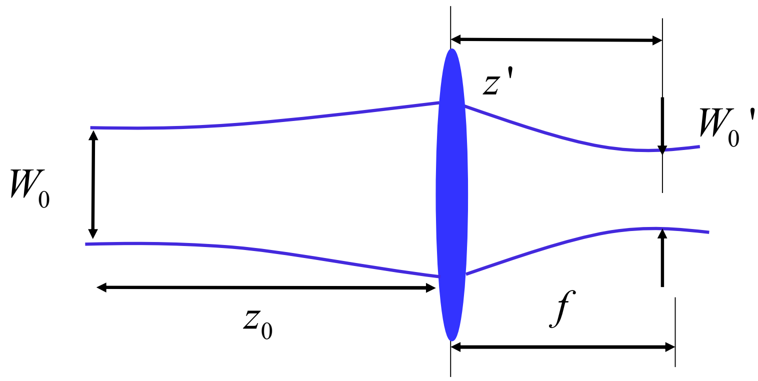
Although geometrical optics (hence optical ray-tracing) suggests that one can focus a beam to a point infinitely small, this is not physically possible as it would violate some quantum mechanics rules.

A important metrics is the Rayleigh length. It defines the height of the focal zone, defined for waist measured at positions $\pm\sqrt{2}w_0$.

Useful formula: Laser beam passing through a lens

$$W_0' = \frac{W_0}{\sqrt{1+\left(\frac{z_0}{f}\right)^2}} \quad and \quad z' = \frac{f}{1+\left(\frac{f}{z_0}\right)^2}$$





Simplified case: (if z_0 >> f)

$$W_0' = \frac{\lambda}{\pi W_0} f$$

$$z' = f$$

A useful formula to calculate the spot size at focus (i.e., waist at focus) for an input beam with a waist W_0.

Important definition related to a laser process

Applied to continuous and pulsed lasers:

- Net fluence in Joule per centimeter sq.: J/cm^2
  - 'How much energy is absorbed in the material for a given unit surface'
- Average power in Watt (i.e. Joule per second) per centimeter sq.: W/cm^2
  - Average energy is absorbed in the material over a unit time

Applies to pulsed lasers:

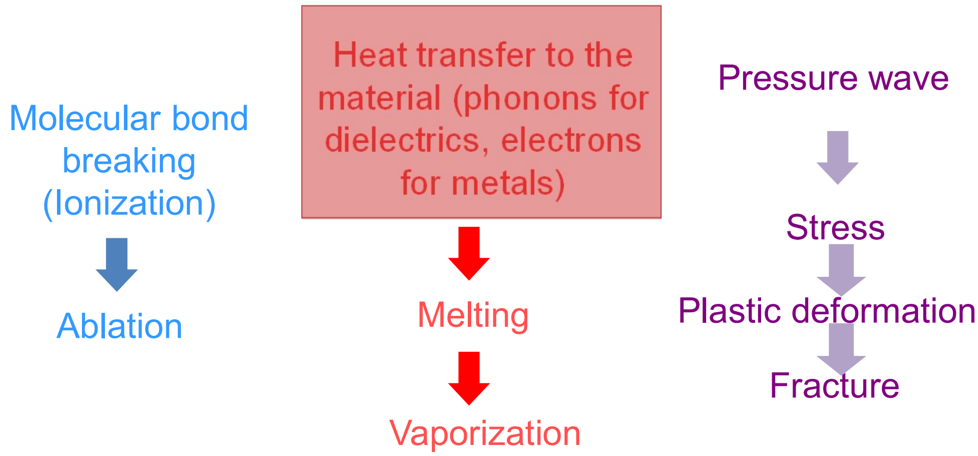
- Net peak power in W/cm^2
  - 'How much power is absorbed in the material *during one* pulse'
- Pulse energy in Joule J
  - 'How much energy is contained in a pulse'
- Pulse duration in s
  - 'How long is a pulse'
- Repetition rate in Hz
  - 'At what frequency pulses are fired'

In laser manufacturing, a set of metrics are commonly used to define the characteristic of the beam.

These metrics, defined above, are useful when developing a laser process to define the laser parameters used and hence, to be able to reproduce certain laser exposure conditions, whatever the laser setup used.

Laser-matter interaction

- A dynamical process: *“how the energy deposited by the laser is ‘digested’ by the material”*



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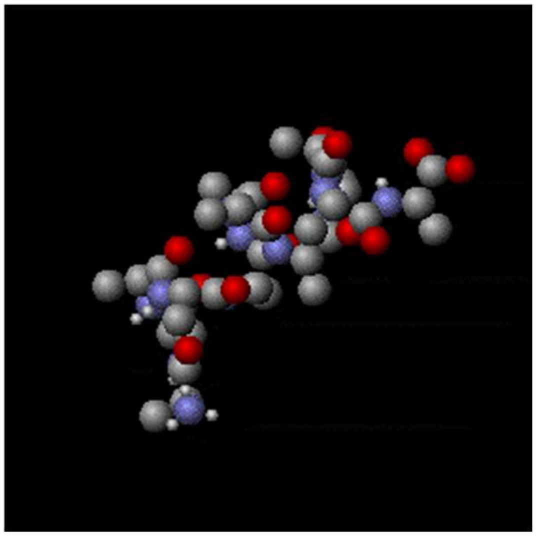
Laser-matter interaction is about understanding how the energy transported by the laser interact with a material.

In the sequel, we will review three main types of interaction that are commonly observed and used.

Interpretation of specific heat capacities



Vibration of a complex protein, source: wikipedia

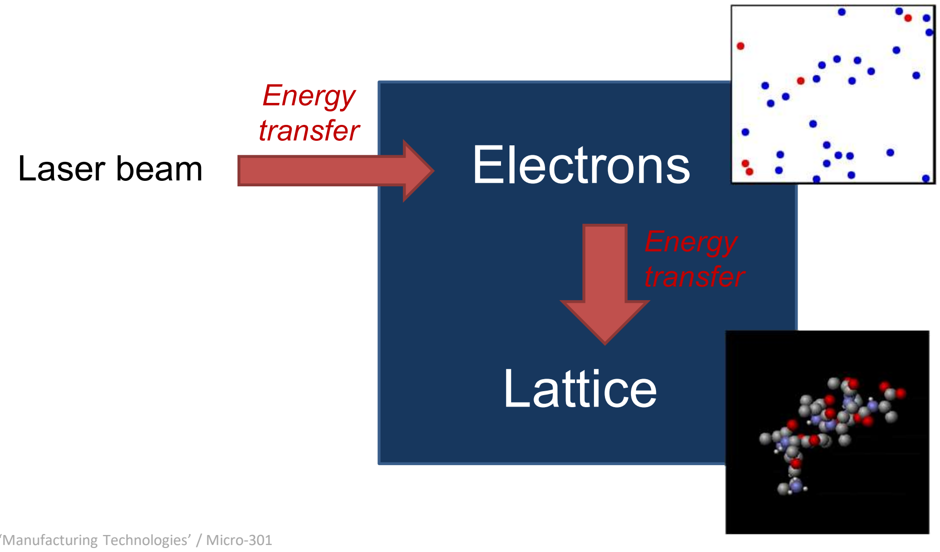
- A metric on how much energy is stored in vibrational/rotational energy
- Each degree of freedom 'absorbs' a certain quantity of energy (equipartition theorem)
- Can be seen as many 'oscillators' with given resonant frequencies

→ Lasers excites molecules vibrations, directly or indirectly

As seen earlier, lasers excite electrons and alter the vibrations of molecules. The vibration of molecules are responsible for the heat capacity of a material.

Interaction of lasers with metals…

In metals, there are ‘free’ electrons to move. (not bonded to an atom)

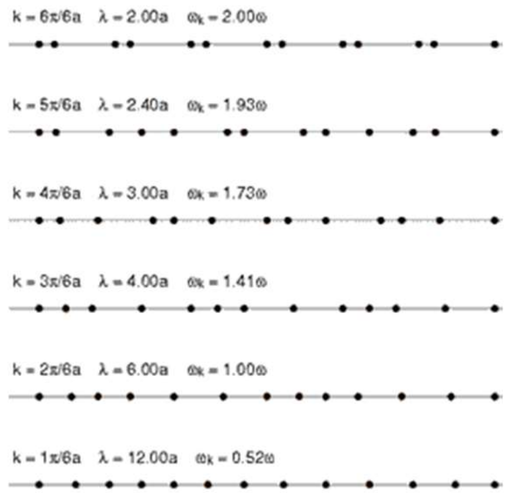


Lasers, being essentially an electrical field, interact with electrons. Hence, laser energy is first transferred to the electrons at a certain rates.

The electrons being excited start to also exchange energy with the rest of the material (the atoms, molecules vibrations, and so on), causing a global heating. Note that this is an efficient means of rapidly heating a material. In general, metals are much better heat-conducting materials than other materials.

In metals, there is a layer of electrons that are free and not bound to a specific atoms. They form a ‘gas of electrons’ that get excited by the laser, which then interact with the lattice, i.e., the rest of the material.

Different means of heat conductions: Phonons vs electrons



(source, R. Lacheaume, 2005)

- **Phonon** = Quanta of atomic vibrations
- Non-conductive materials
- Usually a not so efficient heat conduction mechanism
- In classical absorption, laser excites molecule vibrations

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In non-conducting materials, such as glass or polymers, as electrons are not free and bound to atoms, heat comes in the form of atomic vibrations (phonon).

This is usually a less efficient mechanism for conducting heat. (An exception is diamond, which has the highest heat conduction.)

Thermal transfer: heat equation

$$\rho c\left(\frac{\partial T}{\partial t}\right)=\nabla\cdot k\nabla T+q(x,y,t)$$

Thermal conductivity

Thermal load (on a given domain and for a given time)

Time dependant evolution

Temperature spatial distribution

If **k** is constant, $\nabla\cdot k\nabla T=k\nabla^2 T=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$

Thermal diffusivity

$$\alpha=\frac{k}{\rho c} \quad \Rightarrow \quad \frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right)=\nabla^2 T+\frac{q(x,y,t)}{k}$$

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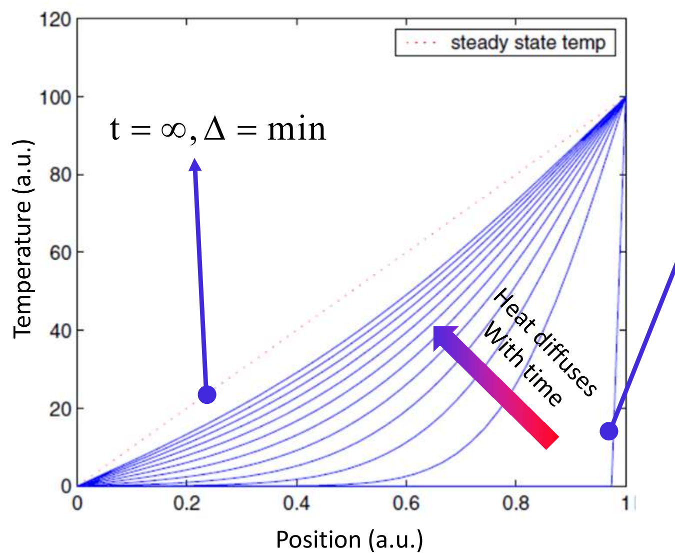
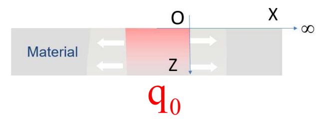
Hence, in the first mode of interaction, which is purely based on considering the laser as a source of heat, the processing can be explained by heat transfer mechanism.

Like for any source of heat, the heat propagation can be effectively described with the 'heat equation'.

The laser input energy is considered as a thermal load. The q(x,y,t) term here.

Intuitive Illustration (one d case)





$$\frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right) = \nabla^2 T + \frac{q_0}{k}$$

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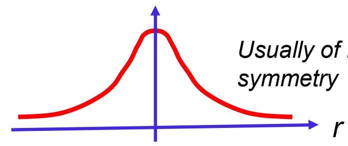
As a reminder of the heat equation as an example of a two-dimensional differential equation, let us consider a one-dimensional case.

Part of the equation, the temporal one, describes how the temperature at a position X along an axis evolves over time, while part of the equation, described how heat propagates along the axis. Hence at a time t=0, 'the hot element' is located at one position and then gradually spreads as time passes, until the extreme case, where it reaches a steady state.

Heat equation

$$q_{x,y,z,t} \propto A(z)\left|E_{x,y,t}\right|^2 \propto A(z)\left|E_{r,t}\right|^2$$



Usually of rotational symmetry

$T(x,y,z,t)$ 'A function describing the temperature distribution in *space* and *time*'

Heat load: laser energy absorbed in the material

$$\boxed{\frac{1}{\alpha}}\left(\frac{\partial T}{\partial t}\right) = \nabla^2 T + \frac{q(x,y,t)}{k}$$

'How fast the heat diffuses'

$$\nabla^2 T = \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

Time dependent, boundary conditions of the equation *(together with the geometrical definition of the problem)*

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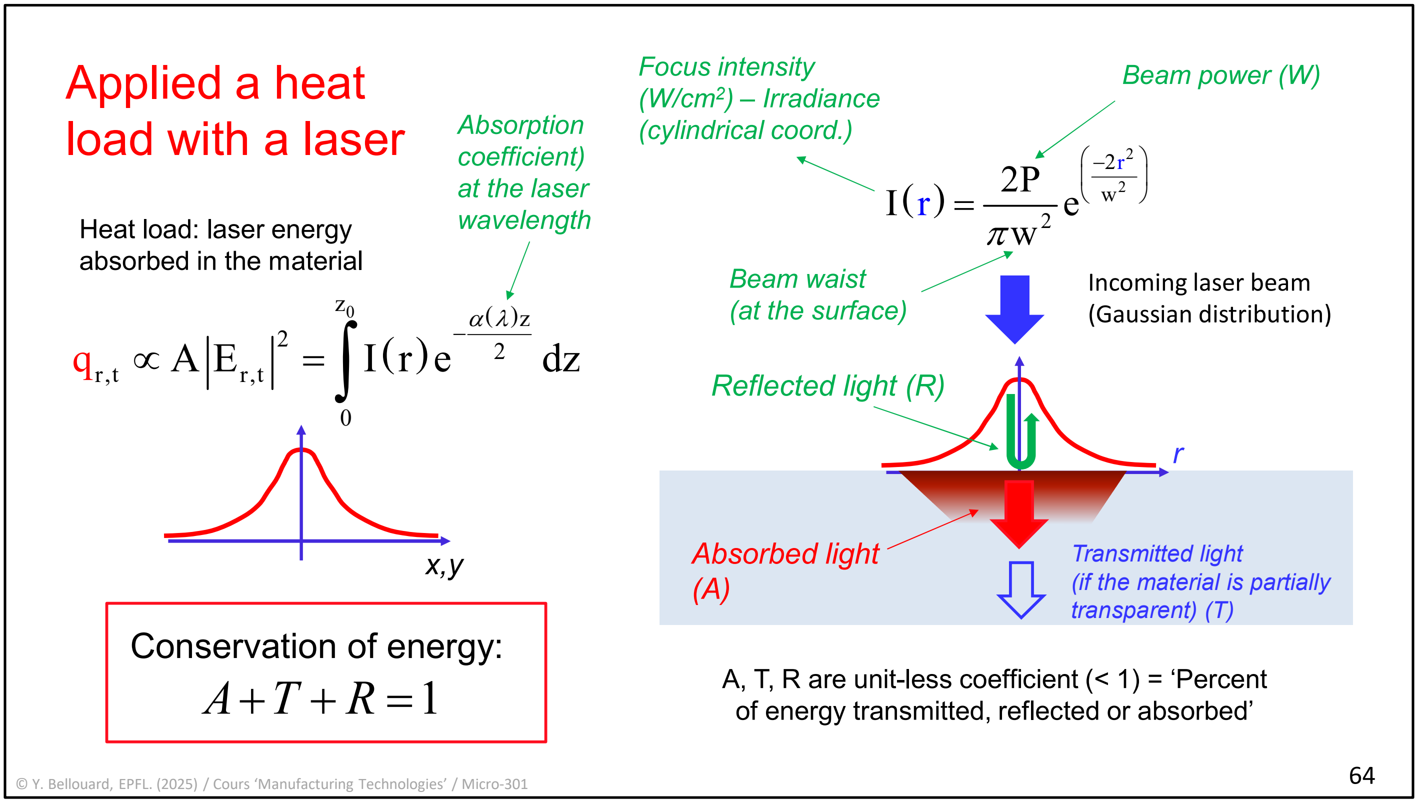
For instance, for a laser impacting a surface, the heat load would be a Gaussian distribution of absorbed energy on a surface.

Apart form the particular heat load distribution, the rest is similar to other heating problems when considering an arbitrary heat source (e.g., a resistor attached to a surface, a torch, a solder iron, etc.).

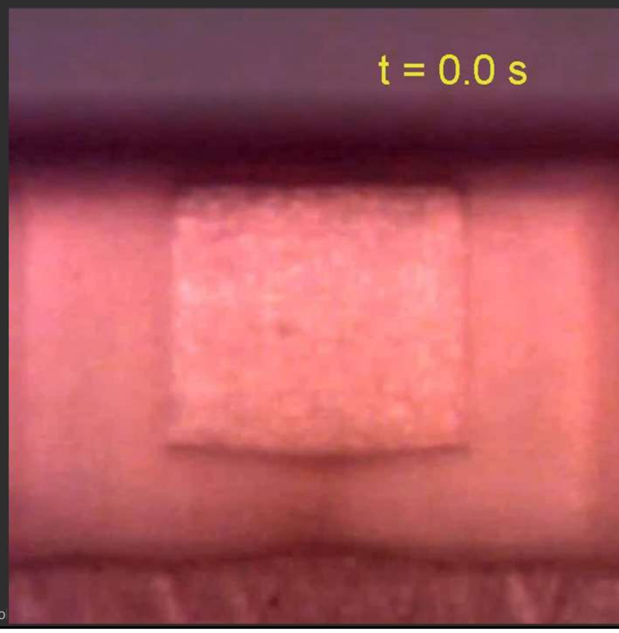


As a laser penetrates in a material, part of it is absorbed, part of it is transmitted (if the material has some level of transparency), and part of it is reflected. Hence the conservation of energy states that the sum of all this energy component is equal to 1.

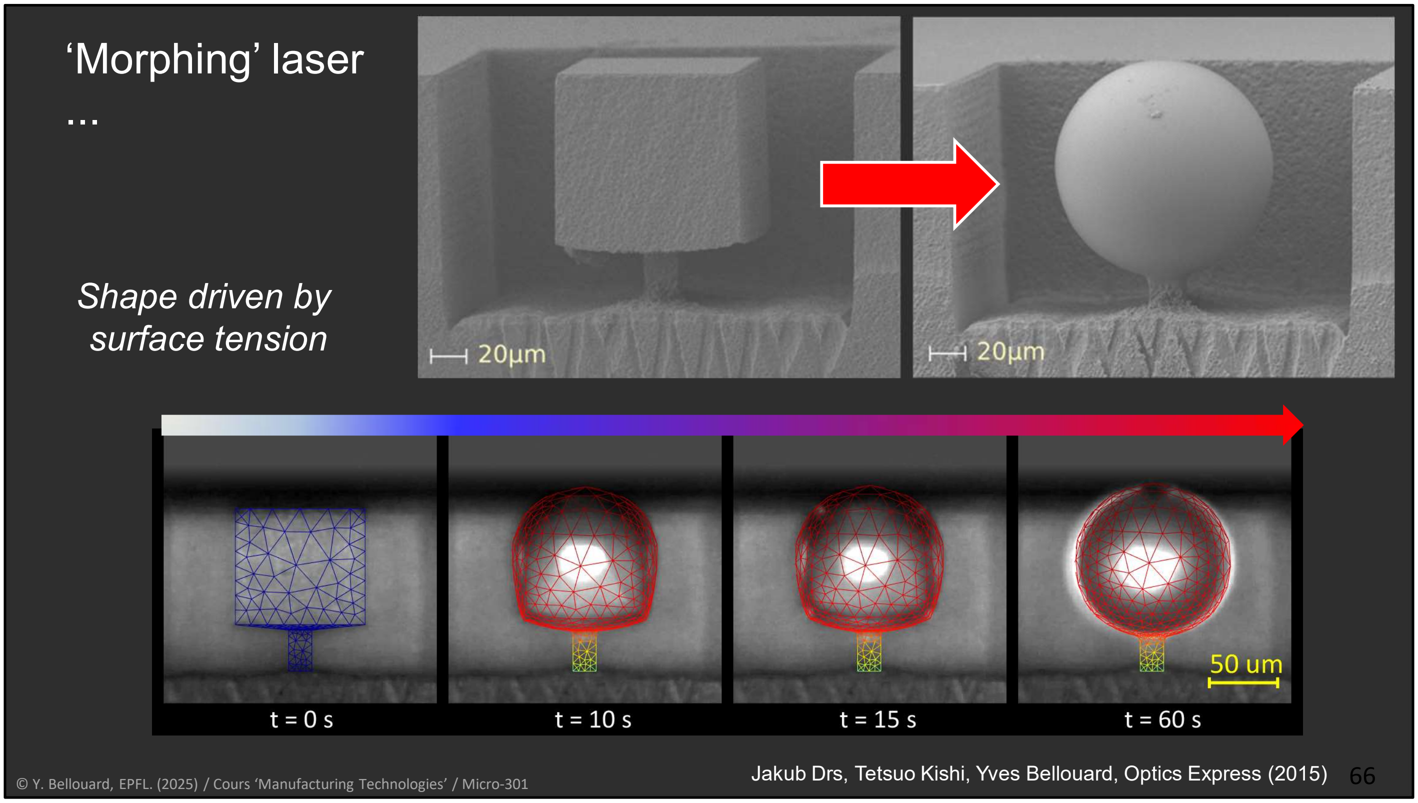
The heat load provided by a laser is the amount of absorbed energy from the incoming laser beam.

The slide above shows how to make the link from a given focus laser beam with a given waist with a thermal transfer problem, at the core of this laser-matter interaction.

Illustration laser-based morphing...



To visualize a practical case, let us consider a real case taken from our own research. What is shown above is a little glass cube (100 microns in size), placed on a little pillar.



Using a laser, we illuminate the cube with a particular laser (an IR laser) for which all the light is absorbed in the material.

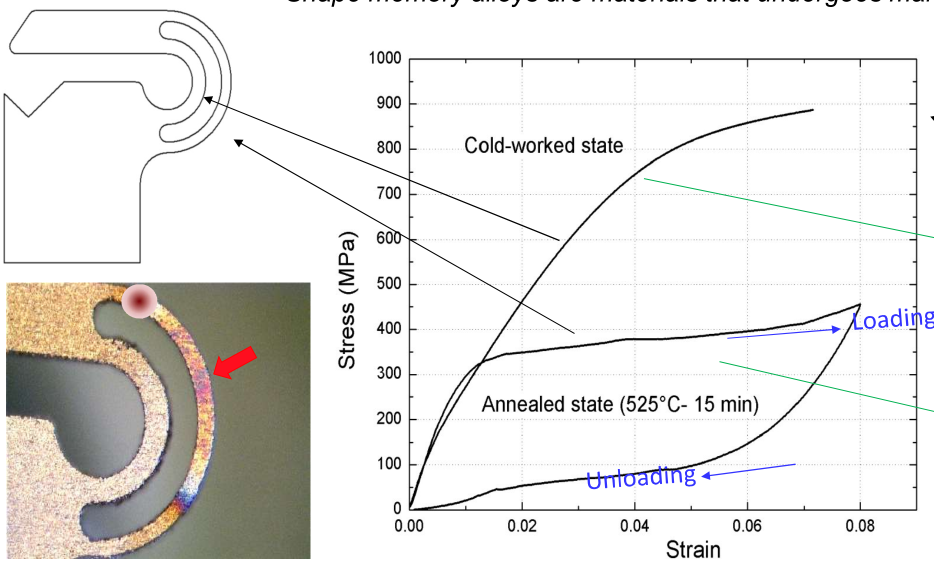
As heat is applied to the cube, it melts gradually and reaches a liquid state. As it becomes liquid, surface tension causes the cube to transform ('reflow') into a perfect sphere, a case that minimizes the surface tension (as seen in previous lectures).

Here, the laser is only used as a means to provide heat locally to the cube. The advantage of using a laser is to be able to heat precisely and rapidly a very small object (here the cube that are 100 um in size).

The temperature exceeds locally 1700 C.

Illustration 2: Laser annealing of Shape Memory Alloys

Shape memory alloys are materials that undergoes martensitic phase transformation



★ The laser is only used for transferring heat to the system

Mechanical characteristic of the material after cold-working (superelastic behavior is blocked)

Mechanical characteristic after annealing (superelastic behavior is recovered)

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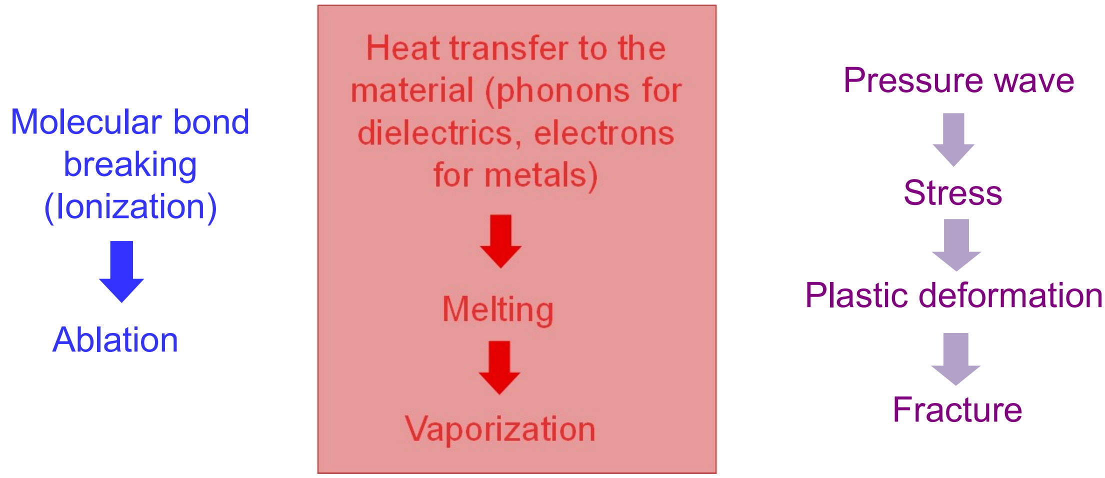
Another example of heat transfer delivered by laser is as shown above. Their the laser is used to induce a local 'annealing' (in French, 'recuit') of a shape memory alloy.

The picture shows a microgripper. The overall size is a less than 1 mm. The little arm shown with the arrow is about 70 microns.

There the laser is scanned over the half-circular outer arms, so that it is thermally-annealed, while the rest remains unmodified. There too, the advantage of using a laser as a heat source (compared to a furnace for instance) is to be able to perform annealing operations only locally and not over the full part.

Laser-matter interaction

- A dynamical process: “how the energy deposited by the laser is ‘digested’ by the material”



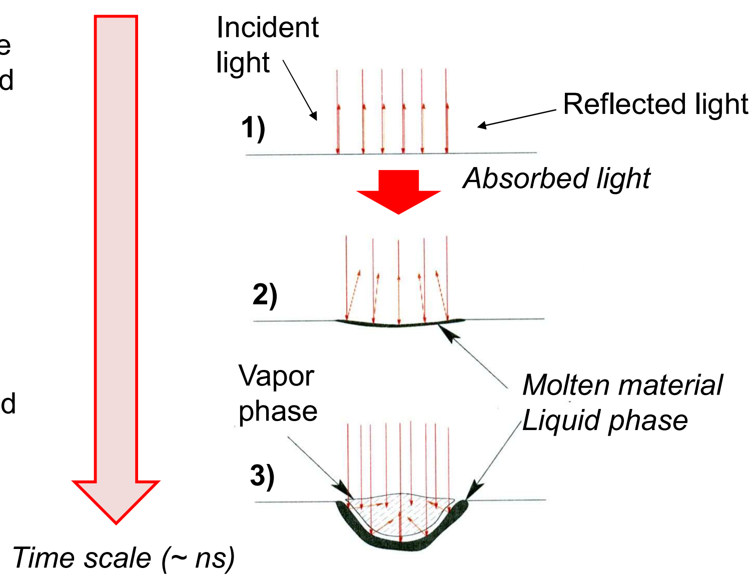
Let us now discuss how this method of transferring heat is used in the context of manufacturing, i.e., for removing material.

Phases during laser micro-machining involving solid-liquid phase transformation

1) Laser energy is absorbed in the volume where light penetrates and then diffuses away

2) Material starts to melt and the surface is modified

3) Liquid may turn into a saturated vapor phase ('plume') that may absorbs itself light.



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As we will see, it becomes a little more complex.

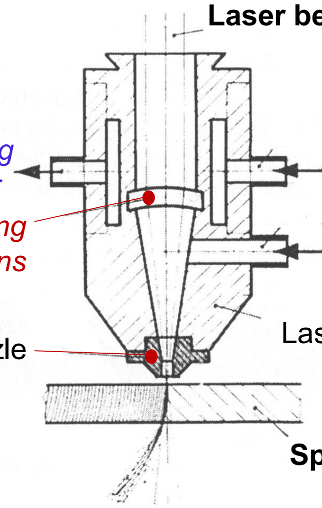
First the laser heat the surface, until the material starts melting. Note that as the material melts, its surfaces orientation changes a little bit, changing absorption properties.

As the materials is heated further, like any material heated high enough, it starts evaporating. The vapor phase form over the surface and itself interact with the laser beam that further modifies the balance of absorbed/reflected energy, and eventually masked the incoming laser beam.

Hence, in this process, a cutting gas is often used to push the vapor away form the laser site.

Industrial lasers (Machining head): how it works in practice?

- **Laser head** and specimen moves relatively one to another
- The cutting gas pushes the molten liquid away from the cut



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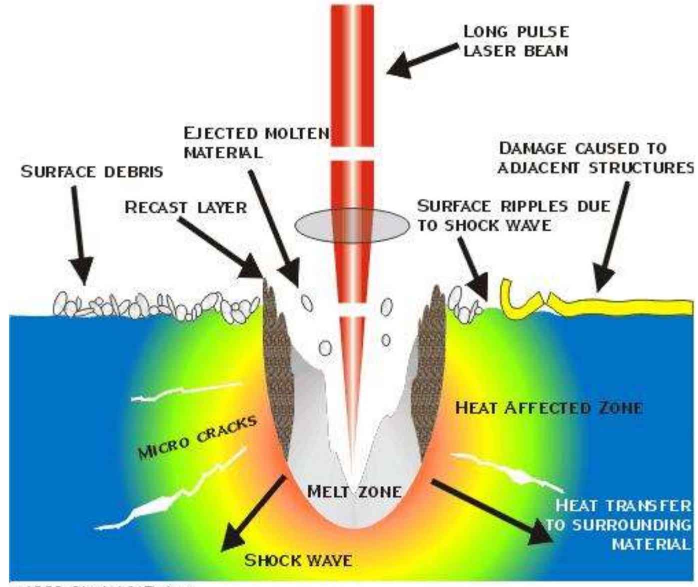
In industrial setting, a cutting gas is used to push the molten material away from the laser site, so that the material beneath it can be itself molten. As a hole is drilled, the laser is further moved along a trajectory to create a cut in the material as illustrated in the image. Note that the image shows an industrial laser typically operating with kW of power.

A schematic of a typical high-power laser head is shown in the right. The cutting gas has typically a pressure close to a bar or higher. Water is used to cool of the head as the focusing lens itself will still absorb a little bit of the incoming laser light and heat by itself, which could cause it to melt as the laser power used in such setup can be very high, up to kWs. So even a few % of absorption can lead to Watts of energy to dissipates.

Materials cut with this method can easily be recognized by a particular texture on the cut side, and usually, by heat-affected zones next to the laser cut.

Laser micro-machining (long pulse)

- Heat transfer outside the region under direct exposure
- 'Heat affected zones'



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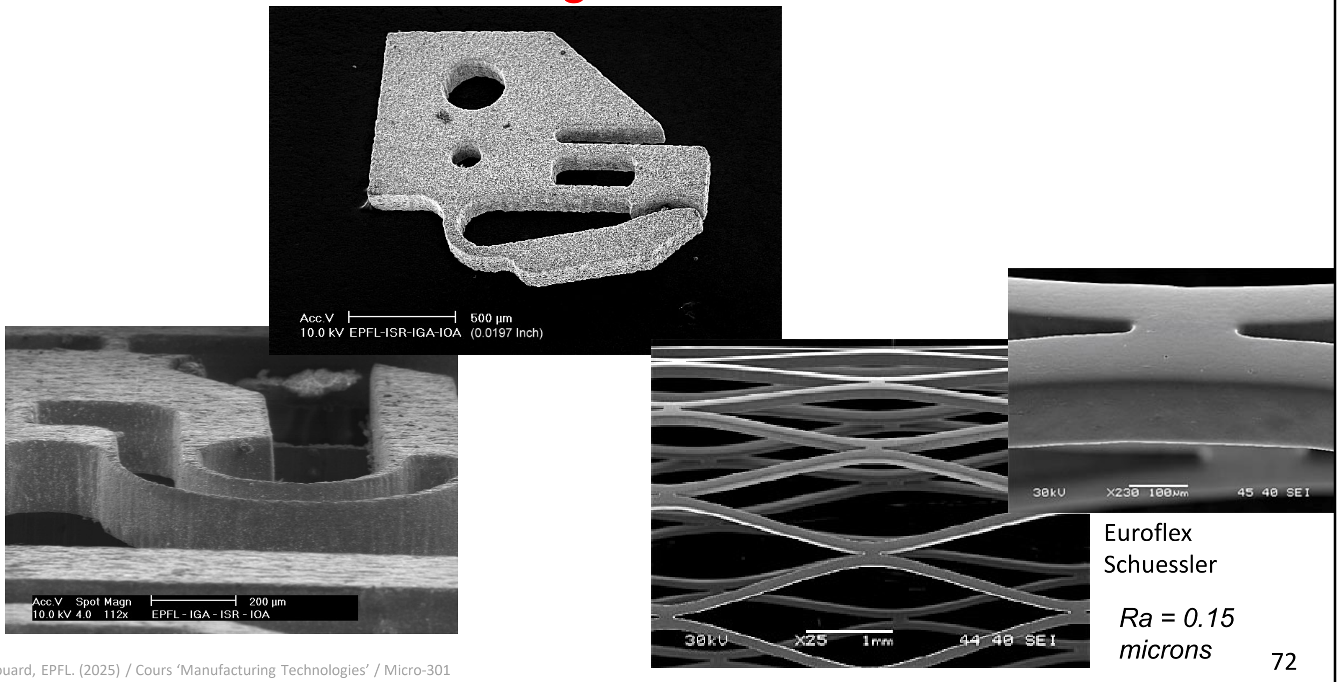
In the example we saw before, pulsed-laser are typically used to allow time for the vapor to dissipate in between pulses, but also to be able to use certain laser technologies that produce high-power pulses.

These pulses are typically a nanosecond long. While this may sound very fast, it is not and remains sufficient for heat to propagates from the laser site and affect the neighboring material. The high-temperature and fast heating can create cracks locally as well as further change in material properties next to the laser site, which is often not desired.

The ideal laser produced cut should be such that the edges quality is as high as possible and that the uncut material remains as undisturbed as possible.

We will see in the follow-up slides that new laser-technologies are emerging that can solve these issues and prevent adverse effects.

Illustration: laser-cutting with a Nd-YAG laser



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The example above is a micro-gripper cut with a pulse IR laser with the method described in the previous slide.

This micro-gripper is just a mm in size. It shows how accurate the laser can be. It is cut out of a Ni-Ti alloy (which is shape memory material).

The bottom-left image shows a close-up view of a cut with a typical texture from the cuts, that testifies from the pulsed-nature of the incoming light.

The bottom-right image is an example of a medical device (a metallic stent used in cardiology) that was cut by laser. The stent as a tubular structure illustrating that laser cutting can be also performed on non-flat surface.

The material was further electropolished to achieve a better surface quality at the expanse of rounding the edges as well.

Laser-matter interaction

- A dynamical process: “how the energy deposited by the laser is ‘digested’ by the material”

Molecular bond breaking (Ionization)
↓
Ablation

Heat transfer to the material (phonons for dielectrics, electrons for metals)
↓
Melting
↓
Vaporization

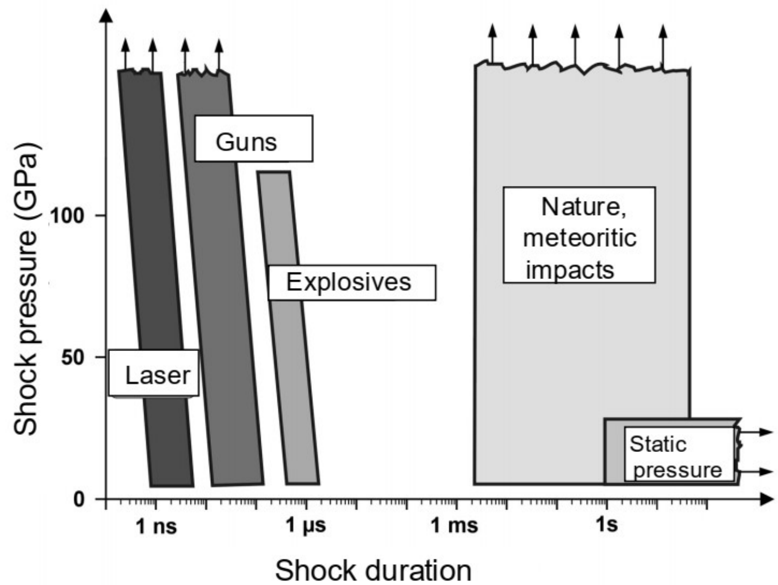
Pressure wave
↓
Stress
↓
Plastic deformation
↓
Fracture

Although lesser known, laser are also used to induce pressure wave on surface, for instance to create hardening effects (‘écrouissage’).

The main idea is that as the energy of the laser is very rapidly absorbed, it creates a fast expansion of the material, just like a shock would do.

Shockwaves

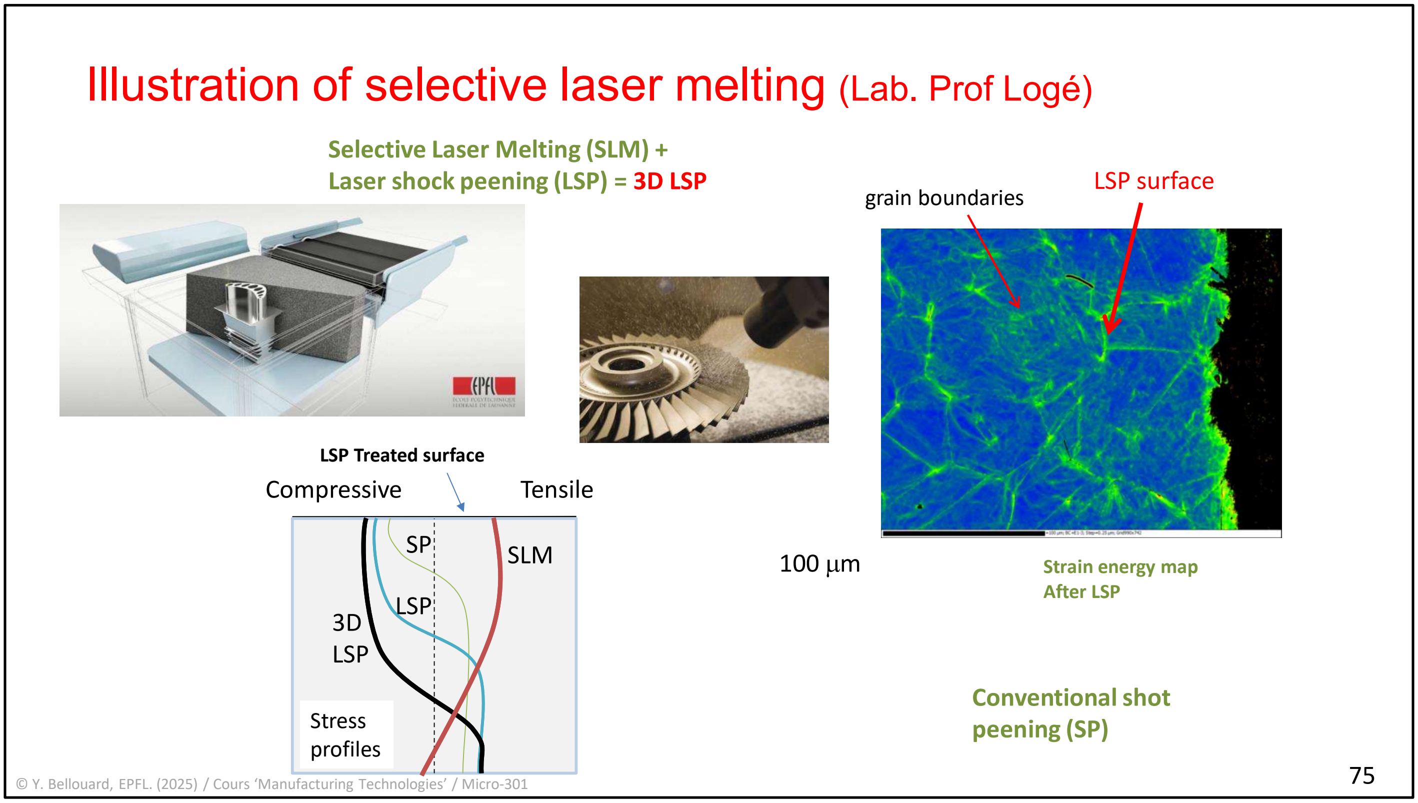
- Rapid absorption of energy
- Rapid expansion of the zone under laser exposure
- Use of sacrificial layer



(source: M. Boustie, et al. Laser Ultrasonics, Montréal 2008)

The graph above compares the time scale of various means to induce a shock-wave and the typical pressure levels that can be reached.

This method typically uses a sacrificial layer (or a liquid layer) that is blasted away and serves as the impactor on the material just below.

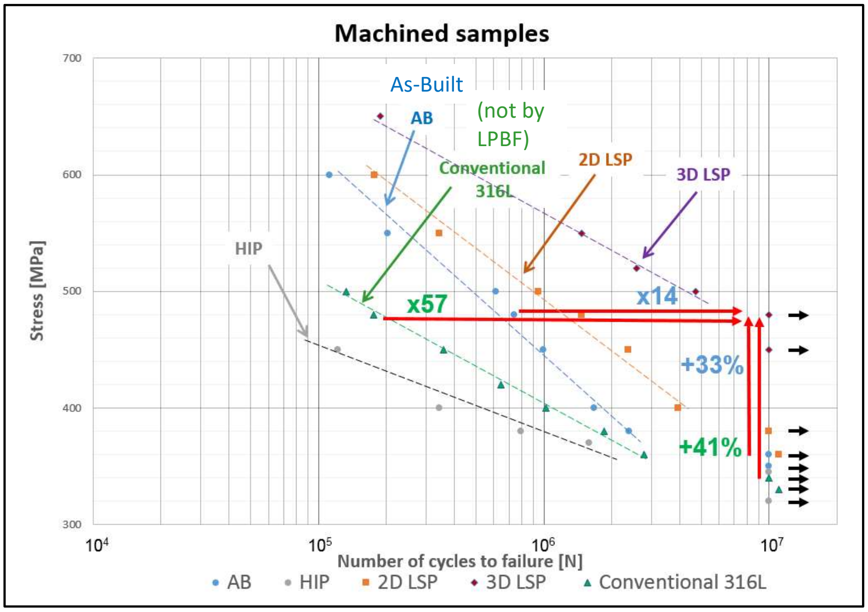


An example from EPFL's research (laboratory of prof. Roland Logé).

Laser-shot peening (laser-shocks) is used to harden layers in three-d printed metal parts through laser sintering. As can be seen in the little graph, SP (as well as LSP and '3D' LSP) creates compressive stress at the surface of the material that makes the material more resistant.

Without doing any laser-treatment, curve 'SLM' on the graph, a tensile stress is observed on the surface, which weakens the material.

Improved fatigue life (beding) – 316Lsteel parts



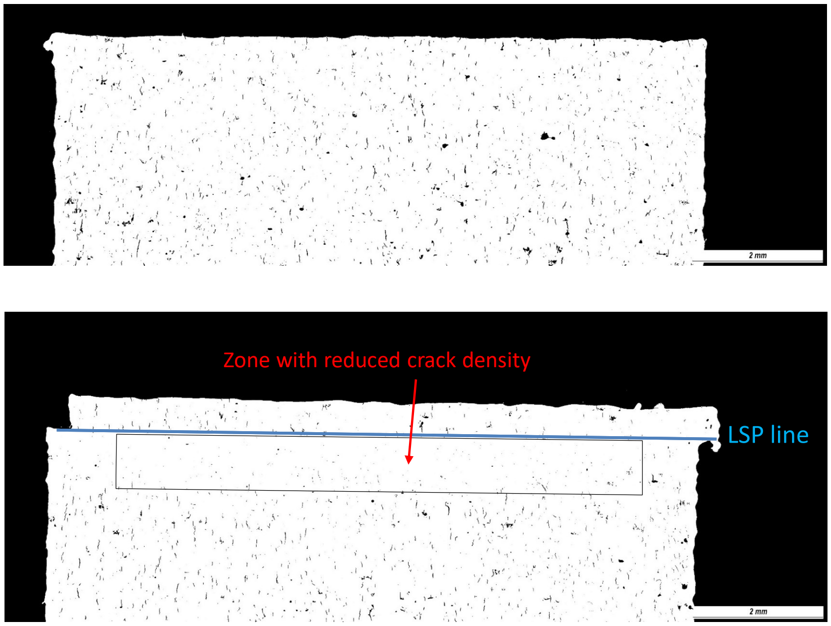
Kalentics et al., *Additive Manufacturing, 2020*

As illustrated here, the laser-shot peening ('LSP') methods improve the overall fatigue performance of materials.

Laser shot peening methods are used in the aerospace industry to reinforce for instance turbine blades. It replaces older methods that were based on ball projectiles or powder blasting.

Laser have the advantage again of being very local and of inducing very high energy transfer, results in very high pressures.

Healing cracks in a Ni-based superalloy



As-built Sample

LSP + 20 LPBF layers on top

Kalentics et al., *Additive Manufacturing, 2019*

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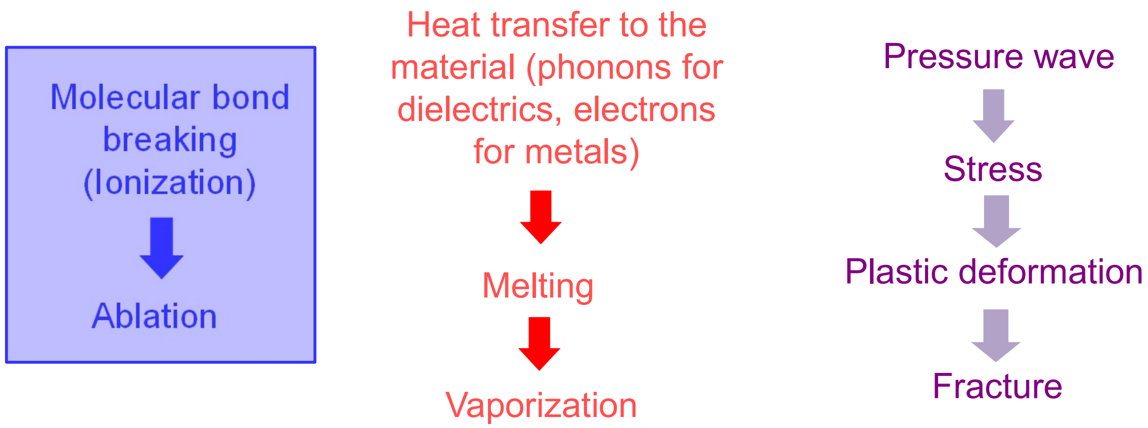
An illustration showing that the zones in a 3D printed metals that have been subjected to 3D LSP get denser.

Laser-matter interaction

- A dynamical process: “how the energy deposited by the laser is ‘digested’ by the material”



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A third interaction mode is one the laser interacts directly with the bonds between atoms, independently of heat effects.

This effect is more complex as it involves light-matter interactions at the atoms level.

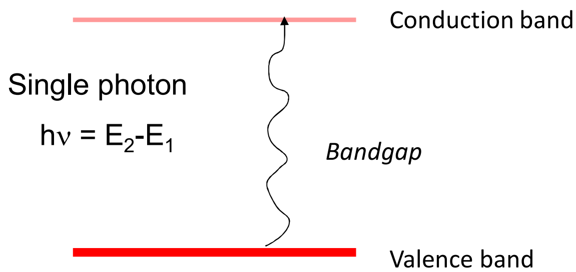
Single photon process

- Photon needs to be energetic enough to directly ionize the material
- Short wavelength lasers (e.g. excimers lasers, frequency tripled Nd-YAG lasers, etc.)

Requires 'energetic photons'

$$E = \hbar\omega = h\frac{c}{\lambda}$$

The shorter the wavelength the more energy...



Example: *to ionize fused silica λ < 200 nm*

Let's consider a transparent material as illustration.

Quantum mechanics tells us that to ionize such material, one would need to provide a photon that *exactly* has the energy of the bandgap of the material. Photons with less energy would not be able to ionize the material as energy is quantified.

This process is called a 'single-photon' process. As we learn about photon, the wavelength of the particle would have to be low if the energy required is high.

For instance, a glass like fused silica that has a high bandgap would need a short wavelength, typically less than 200 nm, which is particularly difficult to produce as a laser.

Concept of ‘multiphotons absorption’: Non-linear absorption

Theoretical discussion during her doctoral thesis (1930), demonstrated 30 years later...

Goeppert-Mayer M (1931). "Über Elementarakte mit zwei Quantensprüngen". Annals of Physics. ***9*** *(3): 273–95.*

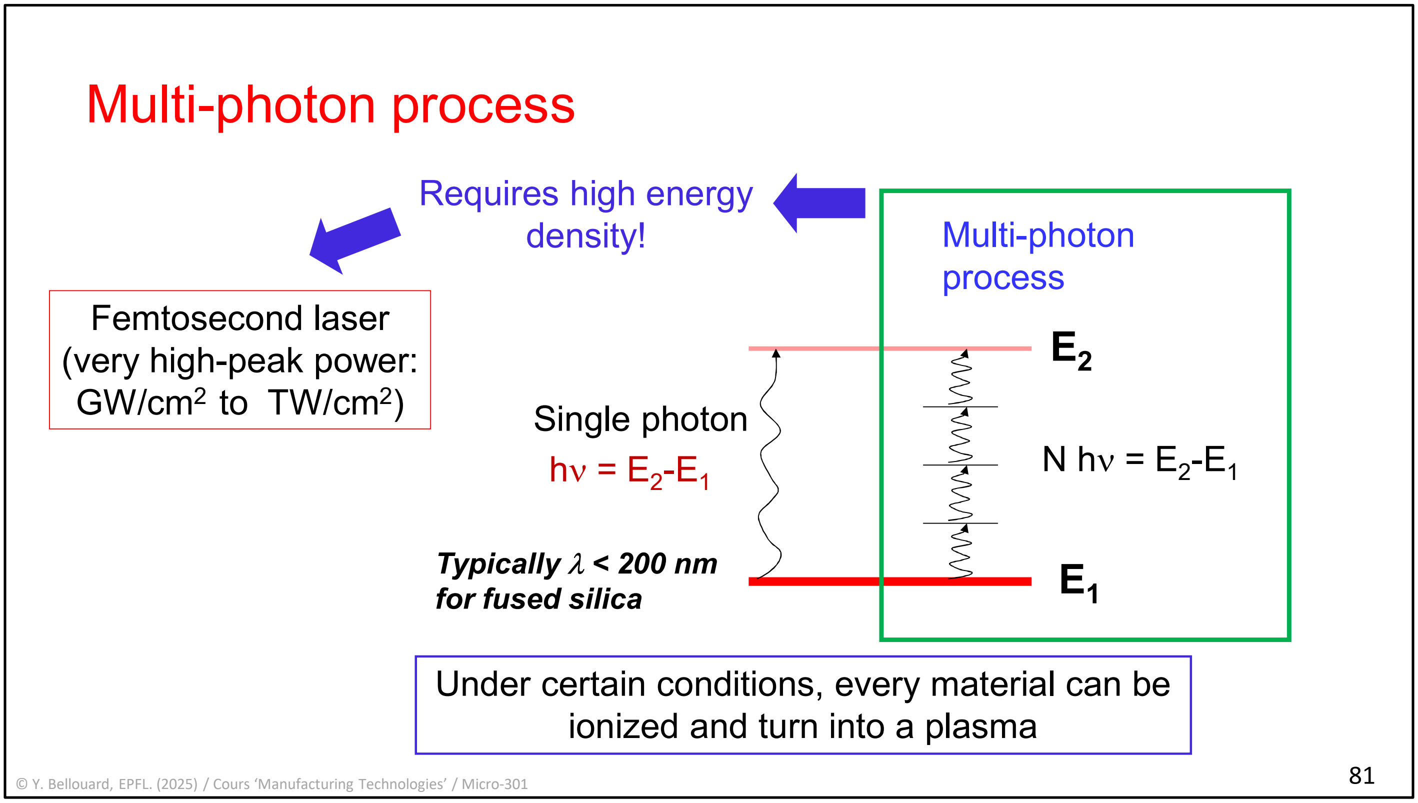
Maria Goeppert-Mayer

Nobel prize 1963 (2nd woman Nobel Prize in Physics)

High photon-fluxes *imply a high probability for two- or more photons to interact* ***simultaneously*** *with an atom.*

In the 1930s, for her thesis, Maria Goeppert-Mayer demonstrated that if the density of photons is high enough, it can happen that the photons ‘team-up’ to induce a ionization effect.

This effect is called ‘multi-photon’ ionization. Maria Goeppert-Mayer got her Nobel prize only in the 60s, because there was no technology available to demonstrate that her claims in her thesis were correct. The demonstration could only be made when lasers were invented as it implies a source capable of generating a sufficiently high density of photons.



In a multi-photon process, the density of photons is such that there is a probability that they 'add' up to provide the energy sufficient for crossing the bandgap for ionization.

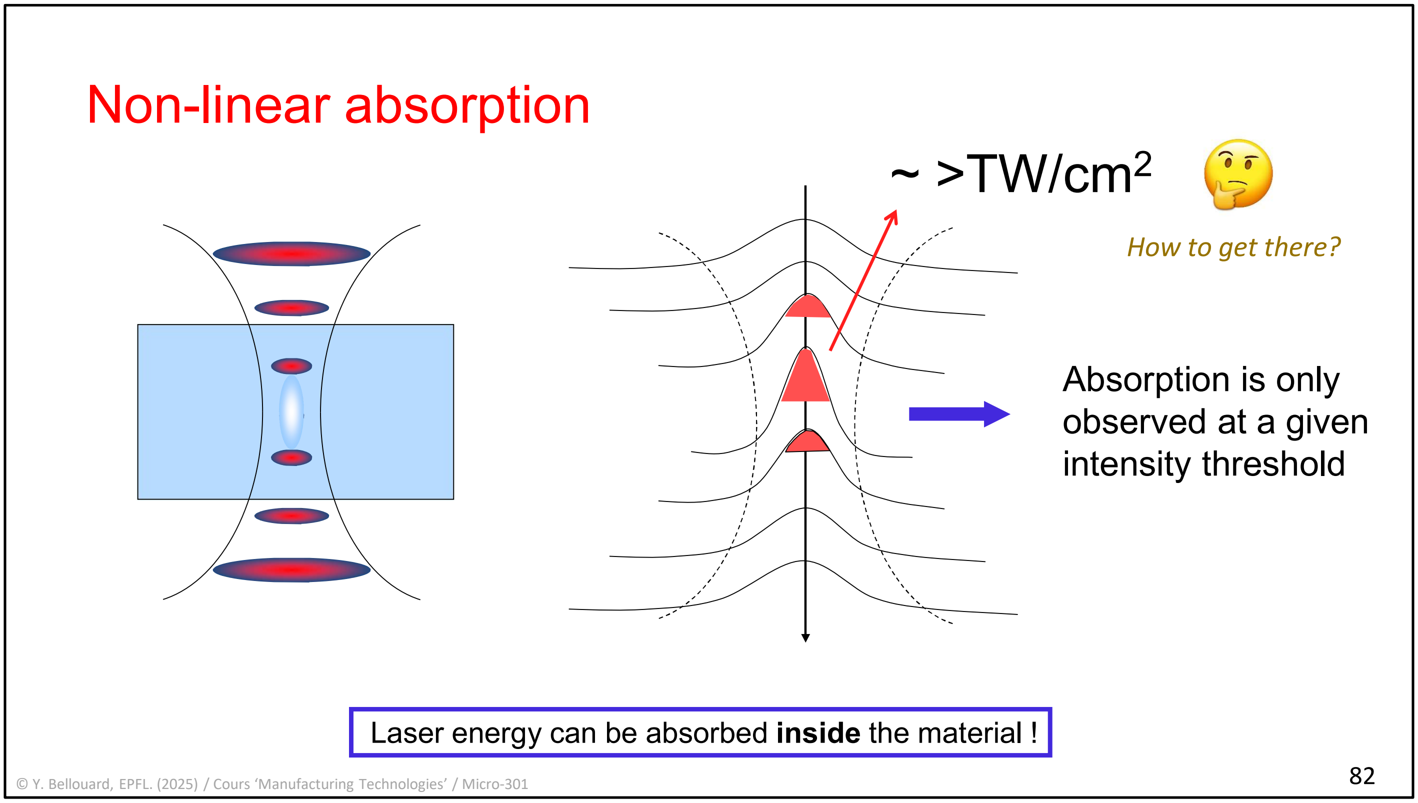
In such case, the band-gap energy can be attained by adding n photons, instead of just a single one, as in single-photon processes.

The main difference is that now, the energy to ionize is not only depending on the wavelength, but also on the number of photons that can pile up.

Technically, it is a major game changer, as should the density of photons be high enough, there will always be the possibility to ionize a material whatever the bandgap is. It may require 2, 3 or more photons, but it can happen.

However, by 'high-density of photons', it means reaching instant power in the order go GW/cm^2 or TW/cm^2! (which is colossal as we will see.)

Such peak power can be reached with ultrafast lasers, and so called, 'femtosecond lasers' that we will explain in the following slides.



This concept of multi-photon absorption is related to the occurrence of a high density of photons.

One interesting aspect of multiphoton absorption is that it is a highly non-linear process. A given threshold of photon density per unit surface needs to be reached to occur.

Looking back at the slides that describes how Gaussian beams are being focused, we noticed that the fluence (intensity / unit surface) very rapidly increase in the Rayleigh zone.

Hence, a laser beam can propagate freely in a material until the density threshold is reached. Consequently, the light energy can be absorbed only at the focal spot of the laser, not before, not after. It offers a means to modify transparent materials in their volume.

Nuclear plant

~ 5-8 TWh

(Olkiluoto, Finland)

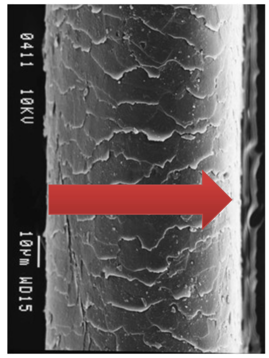
For comparison, a nuclear plant, such as the one in Finland shown above, produces 5 to 8 TWh.

Reaching ~ TW/cm^2 remains possible with yet table-top system. The trick is to consider that here we talk about a power, and hence, an energy (J) multiplies by a time (s). To reach TW level, there is then two options. One is to produce a lot of energy (like in the nuclear plant above), or to 'shrink' the time. In such case, we talk about instant power.

To achieve TW with yet no more than a micro Joule of energy, one needs to shrink the duration of the laser pulse down to the femtosecond regime, i.e., time shorter than 10^{-12} s.

How short is a femtoscond?

≈ 1.26 second



≈ 100 femtoseconds (10^{-13} s)

Among the fastest man-made event!

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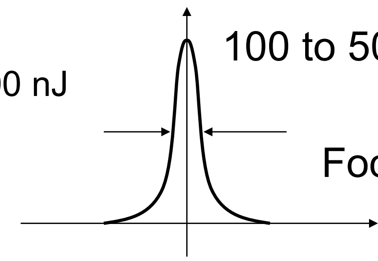
To appreciate how short are femtosecond laser pulses, we recall that it takes about 1.26 s for light to go from Earth to Moon.

Light takes about 100 fs to go across one human hair…

Femtosecond events are among the fastest man-made event.

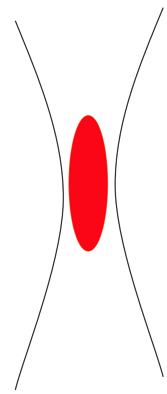
The femtosecond high-peak power (apparent) paradox

Ep = 100-200 nJ
(10^{-9} J)



100 to 500 fs (**10^{-13} s** =0.0000000000001 s)

Focused in a 1 micron surface



Instant peak power:
~ TW/cm^2

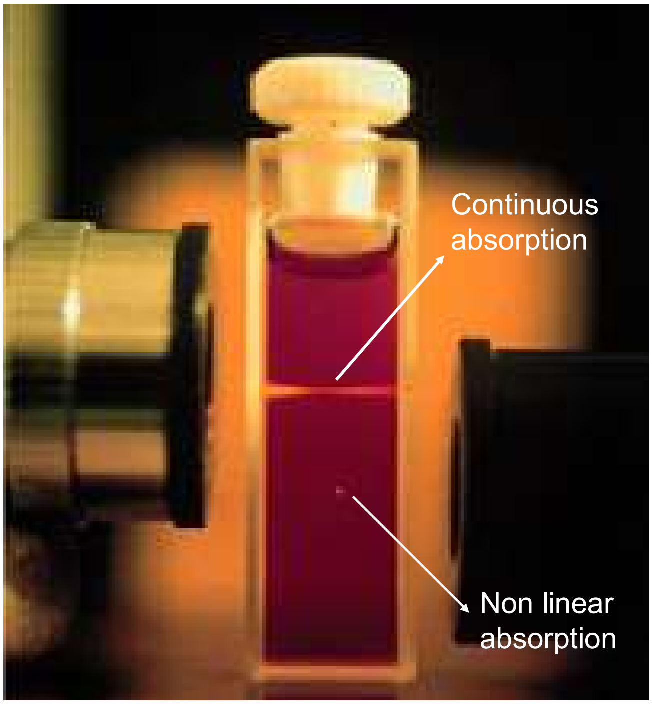
But… the average power is **300 mW**! (@ 800 kHz rep. rate)
Table top / 'miniaturized' laser systems can be used!

Despite reaching extreme peak power (GW to TW per cm^2), such conditions can still be produced with laser sources not exceeding a average power of a few hundreds of mW.

To illustrate this point, let us consider the laser parameters above that are typically used to modify glass material. The pulse energies are in the range of a few hundreds of nJ (hence, 10^{-9} J). Pulse durations are typically 100 to 500 fs. If we focused these pulses on a 1 micron surface (which can be achieved with a microscope objective), then the *peak power* reaches the extreme peak power mentioned above. Yet, if one calculates the *average* power, for pulses emitted at a rate of 800 kHz, it remains as low as 300 mW!

Hence, it is important to distinguish 'peak power' from 'average power', a notion that we are more familiar to. Peak power is the power reached during the duration of *one single pulse.*

This apparent paradox has important some technological consequences. It means that even a laser sources emitting with limited average power, is capable of creating conditions to attain the required peak-power for non-linear absorption, pending that the laser beam is focused tightly and that the peak duration is short enough.



Non-linear absorption in the bulk of materials

- Glass
- Crystals (Diamonds, Sapphire, ruby, etc.)
- Polymers
- …
- Anything transparent!

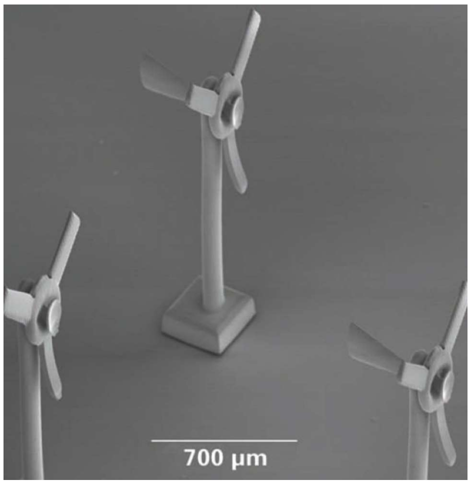
A visual comparison between non-linear absorption and continuous absorption is illustrated on the left image. It shows a vial that contains a fluorescent dye diluted in a liquid.

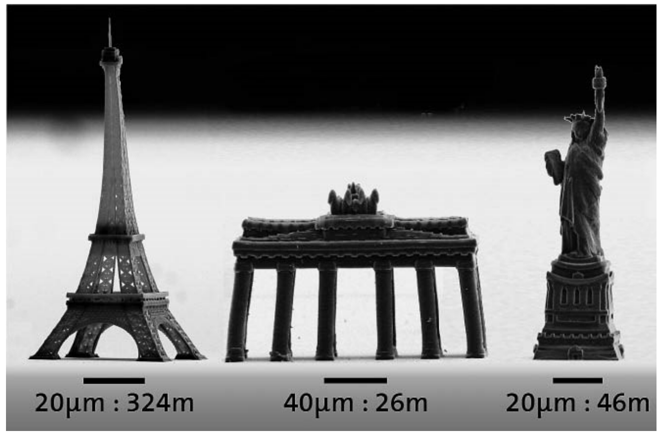
In the case of continuous absorption (above), the light is gradually absorbed as soon it penetrates the liquid and its intensity is gradually reduced as it propagates through the liquid (here from left to right).

In the case of non-linear absorption (below), nothing is absorbed until the intensity reaches a critical value ('a threshold for non-linear absorption'). This value is reached at the focal point only, where the peak power is maximum, and where conditions for multi-photons absorption are met.

Non-linear absorption is quite a universal phenomenon that applies to any transparent materials. However, the threshold power at which it occurs will differ from one material to the other.

Two-photon polymerisation





(source Nanoscribe)

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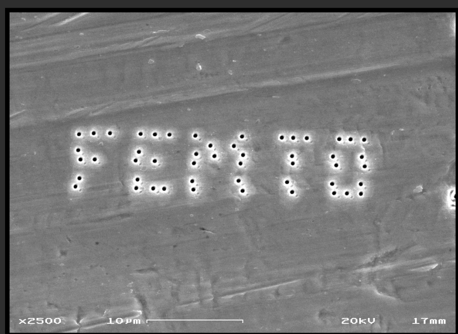
As it is a non-linear effect, based on a threshold, another practical consequence is that non-linear absorption can occur in an area smaller than the spot size itself. Hence, the smallest features sizes are no longer limited by diffraction, and sub-wavelength resolution can be attained.

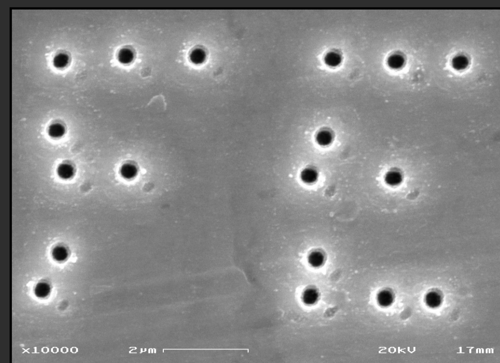
The two examples above are 3D laser-polymerized structure. It illustrates how multiphoton absorption phenomena can be used for 3D printing microstructure of arbitrary complexity.

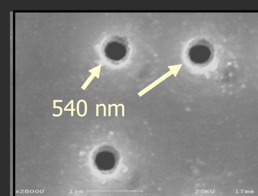
A direct consequence of non-linear absorption mechanisms: sub-wavelength patterning

Holes in stainless steel

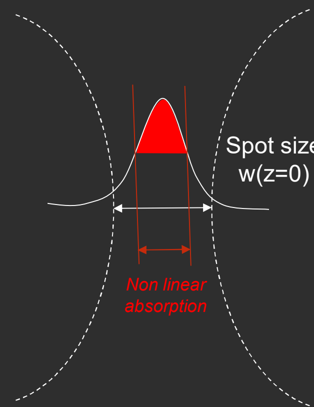


(Source: Eric Mazur, Harvard University)





Example:
Laser spot > 800 nm

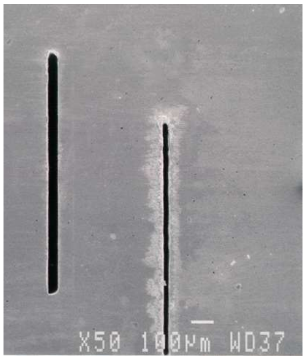


The examples above further illustrate the threshold effects and its consequence on the achievable smallest features size.

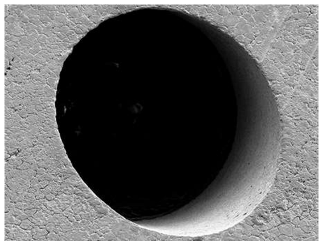
The holes here are smaller than the wavelength of the laser that was used to create it. The explanation is that despite the fact that the smallest spot size that one can achieve while focusing a laser is ruled by the law of diffraction (and will typically be at best in the order of the laser wavelength), in a non-linear absorption even it can still be smaller if the energy above threshold is only the tip of the Gaussian intensity profile as illustrated on the left schematic.

Machining with fs-lasers

- No heat affected zone
- No remolten material
- No cracks



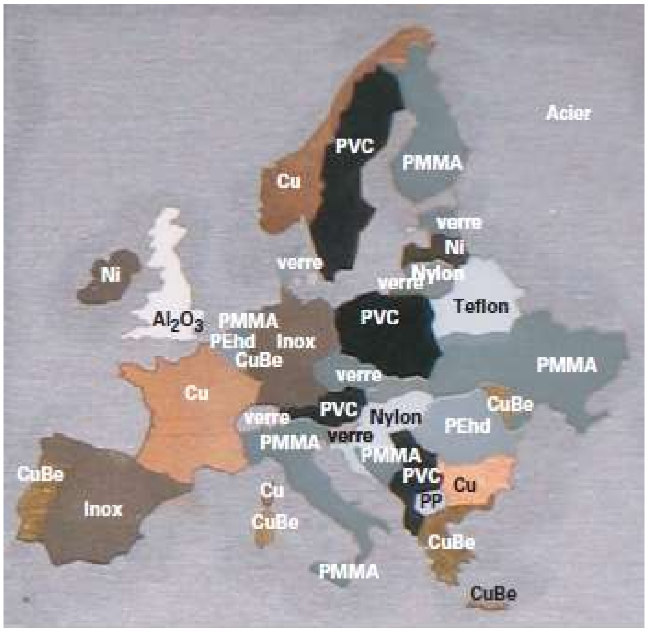
(source Clarck-MXR)



(Images: Trumpf, M. Mielke)

In practice, laser-micromanufacturing with femtosecond pulses offers un precented resolution and cut quality. A noticeable effect is that, unlike usual laser-processing, there is nearly no heat affected zones outside the point where the laser was.

‘Universal interaction’

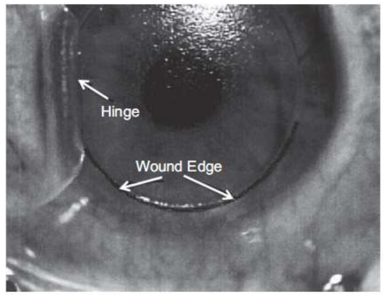


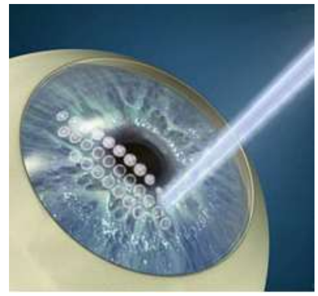
(Illustration E. Audouard & Société Impulsion SA)

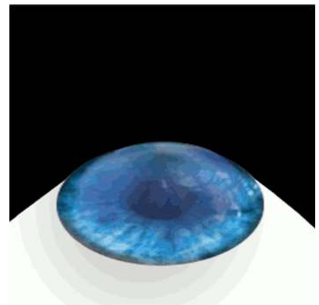
As it involves non-linear effects, the interaction is quite universal. As illustrated above, each country or islands on the European map are made of a different materials, from metal to polymers and from glass to ceramics.

Illustration: eye surgery - 'LASIK' (laser-assisted in situ keratomileusis)

1. Generation of an array of micro-voids inside a transparent medium to lever the flap
2. Open the flap
3. Sculpt the lens





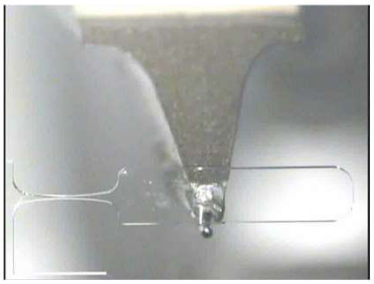


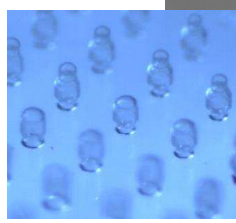
(source animation: Wikipedia)

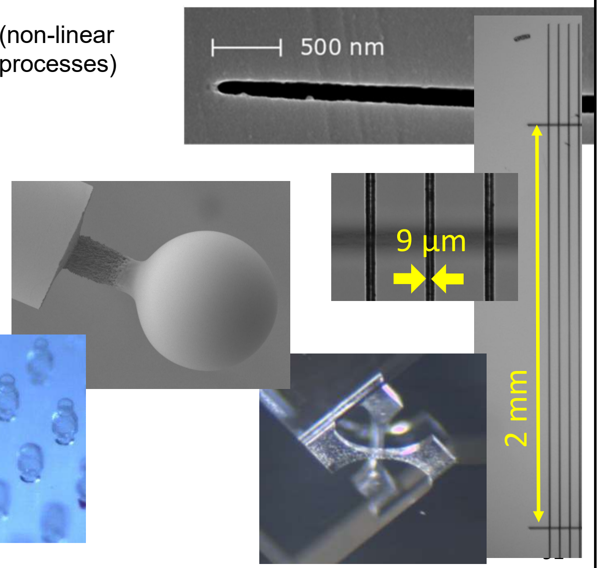
Thanks to its localized interaction, femtosecond lasers are nowadays used in eye-surgery procedures. The laser is used to a flap on the protective layer, so that the cornea can then be sculpted by laser.

Femtosecond laser processing applied to glass micro-manufacturing

- Beyond diffraction limit: nanoscale resolution (non-linear absorption process triggered by multi-photon processes)
- Ultra high-aspect ratio after etching (>1:300)
- Arbitrary 3D shapes
- Scalable
- Roughness Ra < 200 nm or less (morphing)
- High strength mechanical components







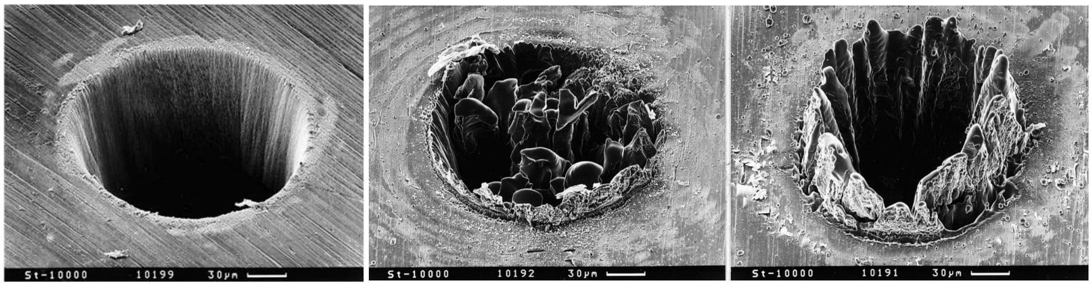
In the context of manufacturing, a very successful application has been for fabricating 3D complex parts with arbitrary geometry, with resolutions smaller than the laser wavelength.

The illustrations above are taken from our own research at the Galatea Lab. It features from left to right, a glass flexure, 100 um-'micro-bottles' made out of polymer and produced using a glass-molding process, a lens fabricated at the tip of telecom fiber (the fiber is 125 um), a nano-channel (top-right) and, a 3D micro-cross pivots (bottom right), and fluidic channels buried under the surface of the glass, just like micro-pipes.

Illustration: ablation of steal at various pulse time scale

Increased pulse duration

200 fs, 120 μJ, 0.5 J/cm^2 | **80 ps**, 900 μJ, 3.7 J/cm^2 | **3.3 ns**, 1mJ, 4.2 J/cm^2



@ 780 nm

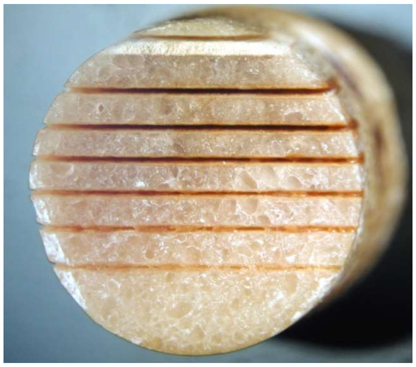
B. N. Chichkov, et al., "Femtosecond, picosecond and nanosecond laser ablation of solids," Applied Physics A: Materials Science & Processing 63, 109–115 (1996).

A key aspect of this interaction is the extreme confinement of the energy and the fact that time-scale of the interaction is such that there is nearly no heat propagating away form the ablation site.

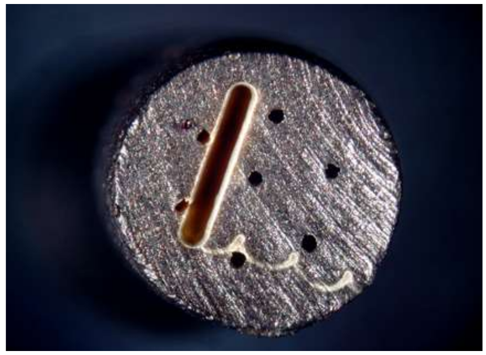
The images above illustrate this point. From left to right, the pulse duration is gradually increase. From the femtosecond regime to the picosecond regime and then the nanosecond regime (roughly applying a factor ~100 on the time duration).

From right to left, in the nanosecond regime, there are evidences of molten material in the ablation crater as well as modified material around the crater, in the picosecond regime, this effect is still present but less significant, and finally, in the femtosecond regime, there is no more evidence of molten material.

A brave demonstration: Safe fs-pulse cutting of explosives and propellants confirms that absorbed energy is removed with ejecta.



Comp B, high explosive



Double-base propellant - HPC-95
Composition: Nitrocellulose - 78%, Nitroglycerin - 21%, other - 1%

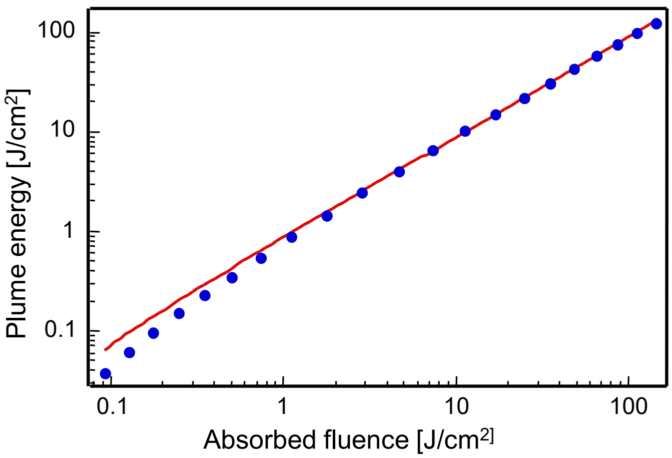
Otherwise, these scientists might not longer be here to tell us about it…

(From E. Roos, LLNL)

As a dramatic illustration of the absence of heat propagating away from the ablation crate, consider the example above from Lawrence Livermore National Lab in the US.

There two highly explosive material are manufactured with a femtosecond laser. Such materials are highly unstable, but nothing happens as the laser energy remained confined in the ablated material ('the ejecta').

A specificity of ultrafast-laser interaction: ejecta remove nearly all absorbed energy !



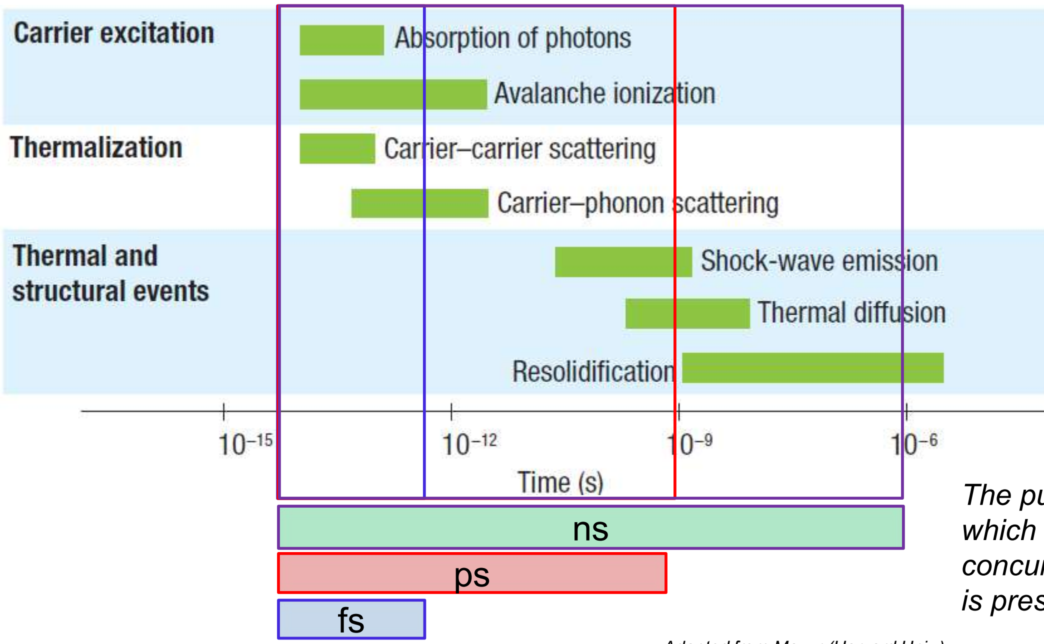
- Plume energy P and absorbed energy fluence F are linearly related beyond a fluence threshold.
- Nearly 90% of absorbed energy is ejected with plume.

Aluminum; pulse duration = 120 fs, $\lambda = 826$ nm, $\theta = 45^0$, p-polarization

Source : M.D. Feit, A.M. Komashko, A.M. Rubenchik, Lawrence Livermore National Laboratory

The last point is further illustrated here in a curve that shows that nearly all the absorbed energy is going away in the 'plume', i.e., the material ejected from the laser exposed site.

Typical time scales



Light = electrons interaction

Thermal transfer at the atomic level

'Material scale' Thermomechanical effects

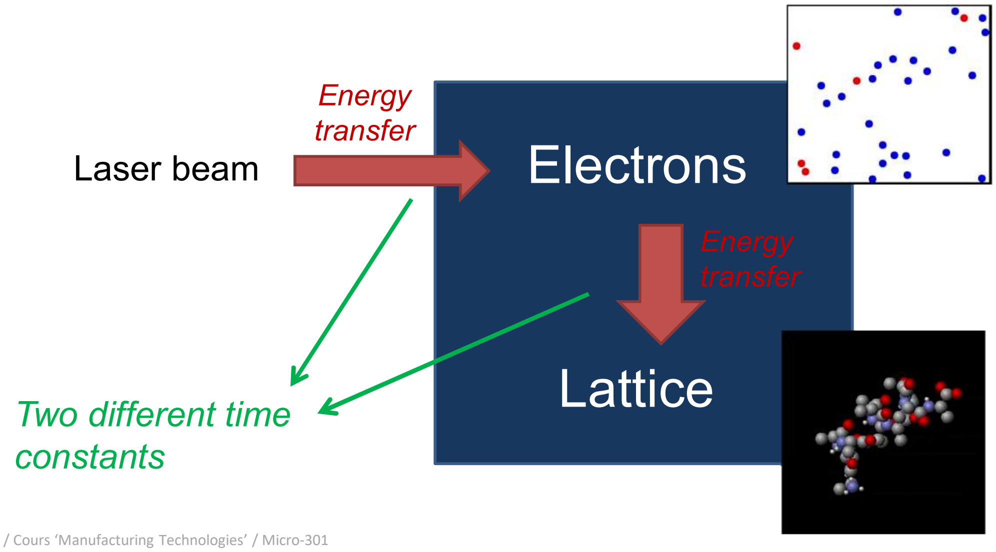
The pulse duration controls which events can occur concurrently when the laser is present!

Adapted from Mazur (Harvard Univ.)

In addition to the non-linear nature interaction described in the previous pages, a key features of ultrashort pulse lasers is the fact that the pulses have length-scales that are comparable to some early physical phenomena triggered by the light passing through the material, and are much shorter in time, than typical timescale for thermal diffusion for instance.

Interaction of lasers with metals…

In metals, there are ‘free’ electrons to move. (not bonded to an atom)



For instance, in the schematic illustrating the interaction of a laser beam with a metal, the time scale for transferring energy from the laser beam to the electrons is much faster than the time scale for electrons to transfer their energy to the lattice.

In the case of femtosecond laser, unlike with longer pulse lasers, the pulse duration will typically be in the same order than the time scale to transfer energy from the photons to the electronics.

One-dimensional: Two-temperature diffusion model

Hear diffusion constant

$$Q(z) = -k_e \frac{\partial T_e}{\partial z}$$

T_e = Temperature of the electrons

T_i = Temperature of the lattice

Electrons

Coupling term

'heat capacity of the electrons'

$$C_e \frac{\partial T_e}{\partial t} = -\frac{\partial Q(z)}{\partial z} - \gamma (T_e - T_i) + S$$

'heat capacity of the lattice'

$$C_i \frac{\partial T_i}{\partial t} = -\gamma (T_e - T_i)$$

$$S = I(t) A \alpha \cdot e^{-\alpha z}$$

'Laser source'

'Lattice'matrix

A model to take into account the different time constant for the 'electrons heat transfer' and the transfer of energy from the electrons to the lattice (i.e., the rest of the material structure).

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To model this effect using modified heat-transfer equations, a common approach is to consider two different temperatures: a temperature for the electrons and a temperature for the lattice, just like if two materials of very different heat capacity were present.

Modelling laser-matter interaction in the femtosecond laser exposure regime is therefore particularly complex and an ongoing hot-research topic.

‘Material Removal Rate’
Example of empirical law

$$\frac{\dot{V}}{P_{avg}} = \frac{1}{2}\frac{\delta}{\phi_0}\ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

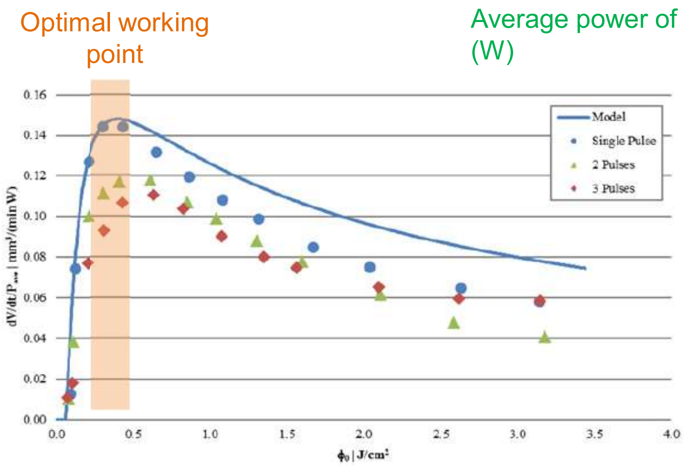
Material removal rate (dV/dt)

Average power of the laser (W)

Penetration depth

Net fluence (W/cm²)

Absorption fluence threshold



B. Neuenschwander, et al., Phys. Procedia **56**, 1047–1058 (2014).

However in practice, empirical laws have been established to assess the material removal rate as a function of key laser-exposure parameters, such as the average power and the fluence.

An example of empirical law is shown above and is discussed further in the follow-up page.

An interesting, perhaps counter-intuitive first observation, is that the optimal ablation removal rate is achieved for a given fluence, but decreases if higher fluence is reached.

Parameters influencing the machining process

- Pulse duration
- Energy in the pulse
- Focusing conditions
- Polarization of the laser
- Repetition rate (how often the laser pulse is emitted)
- Processing speed

Pulse duration, energy in the pulse, focusing conditions → Control the net fluence (W/cm^2)

Polarization of the laser → Local structural effects (orientation of the electrostatic field)

Repetition rate, processing speed → Production rate

$$\frac{\dot{V}}{P_{avg}} = \frac{1}{2}\frac{\delta}{\phi_0}\ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

Material removal rate (dV/dt)

Average power of the laser (W)

Net fluence (W/cm^2) => Incoming laser light

Material parameter

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In micro-manufacturing with ultrafast lasers, there are a few parameters that control a manufacturing process. The pulse duration, the energy in the pulse and the focusing conditions (e.g., how tightly is focused the beam) control the net fluence (W/cm2), i.e., how much power of energy is deposited on a given surface.

The polarization of the laser (i.e., the orientation of the electrical field) controls local structural effects. Finally the repetition rate (i.e., how often the laser pulses are emitted) and how fast is the laser beam moving on a trajectory control the production rate.

In the empirical law mentioned before, there are two material parameters (the penetration depth and the threshold fluence for non-linear absorption). The other parameters are related to the laser exposure conditions.

What is the optimal laser for a given application?

1. Depends on the task
   - Material heat treatment (Annealing, oxidation, etc.) → Transfer heat, but without structural modifications
   - Material removal
     - Throughput → High fluence
     - Quality
     - Resolution
       } Small waist size (shorter wavelength), limited laser-affected zone
     - Selectivity → Non-linear process

2. Technological availabilities of lasers
   - Ouput power capabilities
   - Pulse duration
     } Laser-technology availability
   - 'Cost of the photon' → Laser-technology efficiency, cost of the components

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Coming back to laser manufacturing in general, a question that arises is to find out what is the optimal laser to use for a given application.

Unfortunately, there is not a single answer and it is as usual an optimization multiparameter problem.

Indeed, it depends on the manufacturing task considered. If the goal is to achieve a heat treatment (like an annealing as illustrated before), certainly one will want to promote *linear* absorption and consider laser-matter interaction for which there is no ionization taking place, but only a pure heat transfer.

If it is about to remove materials (like for machining parts), there are also multiple choices depending on the processing requirements. If high-throughput processing is required (i.e. high productivity/efficiency), one will look for high-fluence levels.

If the quality of the cut and the resolution are particularly relevant parameters, small waist size (hence, shorter wavelength, strong focusing) and non-linear processes will be favored to achieve selectivity and high resolution.

Finally, a economical parameter is how costly is the choice of lasers for the task. The cost of a laser source (as well as its operating cost) can vary significantly. For instance, as of today, CO_2 or Nd-YAG are rather low-cost compared to femtosecond lasers. At the end, it will be a matter of optimizing cost versus process requirements.

Selecting a laser…

Type of laser operation	Typical laser choice
Thermal treatment	Continuous Wave lasers (CW) – IR Lasers / Long pulses (~ ms)
Mechanical treatment / shock peening	Short pulse laser (ns)
Machining through melting / liquefaction / vaporization cycles / High throughput	High power / Low cost / CW lasers (CO_2) Fibers lasers / nd-YAG lasers (ns)
Micro-machining through direct ablation	Excimer lasers (UV) / Ultrafast lasers (picosecond, femtosecond)
Welding	Thermal process > various lasers Glass-to-glass > Ultrafast lasers (Non-linear absorption)
Engraving / marking	Broad range of lasers / depends on the type of marking (from CW lasers to ultrafast lasers)

Taking into account all the considerations discussed before, the table above lists typical choices of laser as a function of the manufacturing tasks.

Wrap-up / Things to remember

- **Understand how laser transfers energy to a material**
  - Dynamics of the laser interaction (time scales)
  - Electromagnetic description of light-matter interaction (Lorentz model)
  - Refractive index and coefficient of absorption of a material
  - Absorption processes (linear vs non-linear)
  - Laser-manufacturing modalities
  - Energy dissipation (mechanical, bond-breaking, heat-transfer, etc.)

- **Key concepts related to a laser**
  - Wavelength vs photon energy
  - Pulsed versus continuous
  - Gaussian beams
  - Types of laser versus applications

This lecture contains complex notions and a broad overview of the topic.

As a wrap-up, key notions to remember related to how laser manufacturing are listed above. For an exam, we will consider the listed points above as known and understood.