Lasers

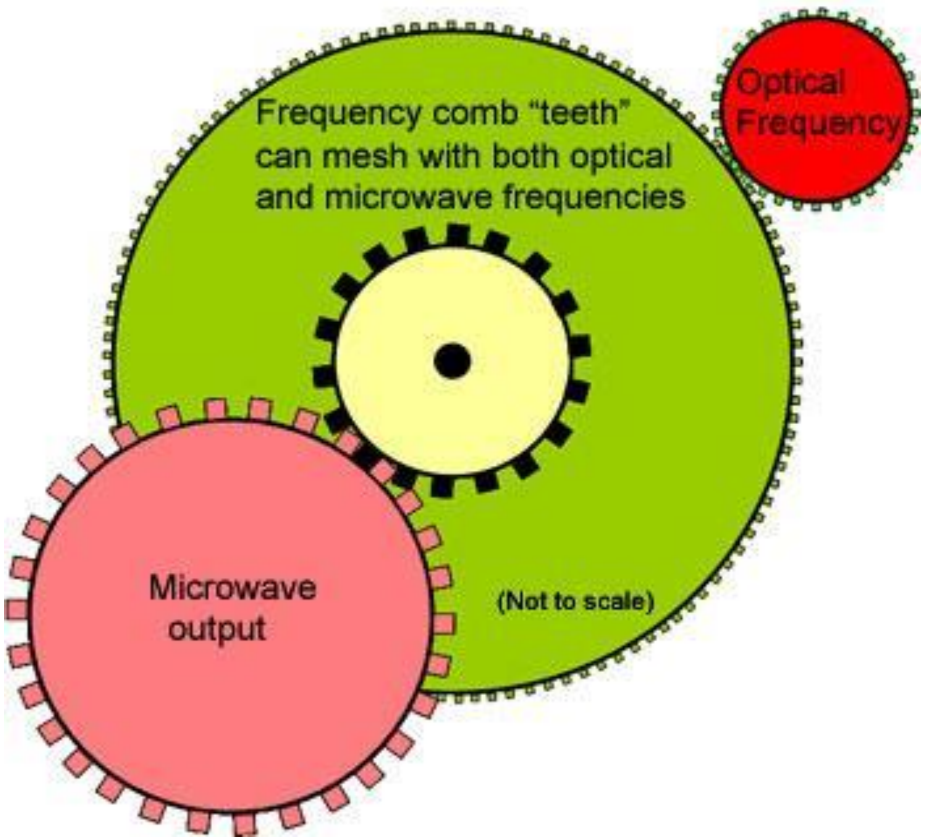
lecture 14

Czesław Radzewicz

optical frequency comb (OFC)

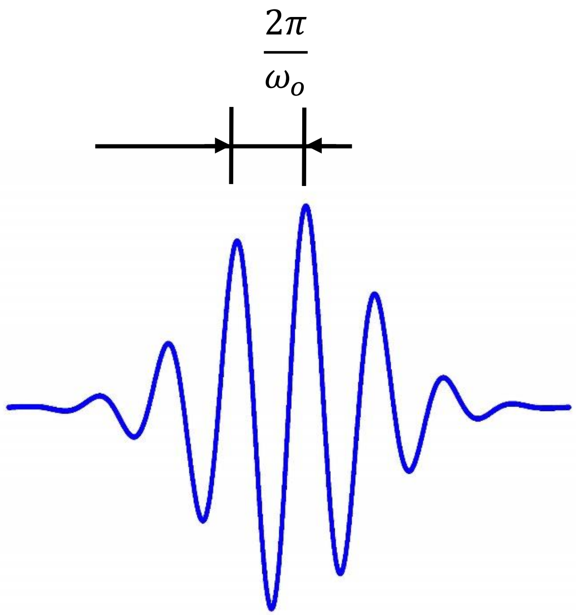
radio-frequencies (RF) $10^7 \div 10^9$ Hz
microwaves $10^9 \div 10^{11}$ Hz
………………
optical range $10^{14} \div 10^{15}$ Hz

required reduction approx. 10^4

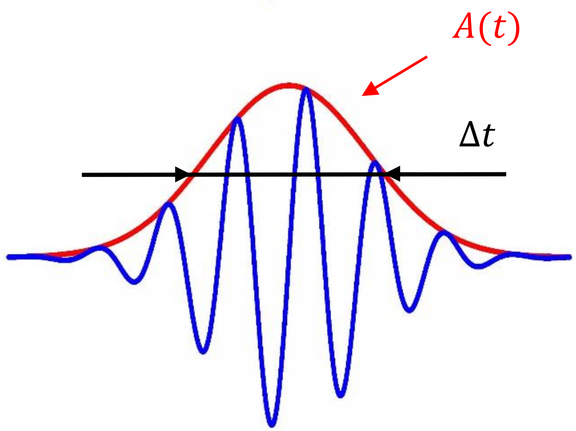


source: www.nist.gov

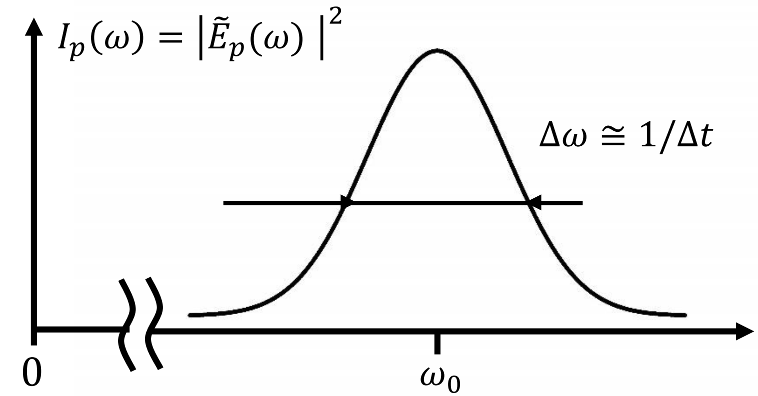
a short light pulse



$E_p(t)$



$$E_p(t) = A(t)e^{i(\omega_0 t+\varphi)}$$

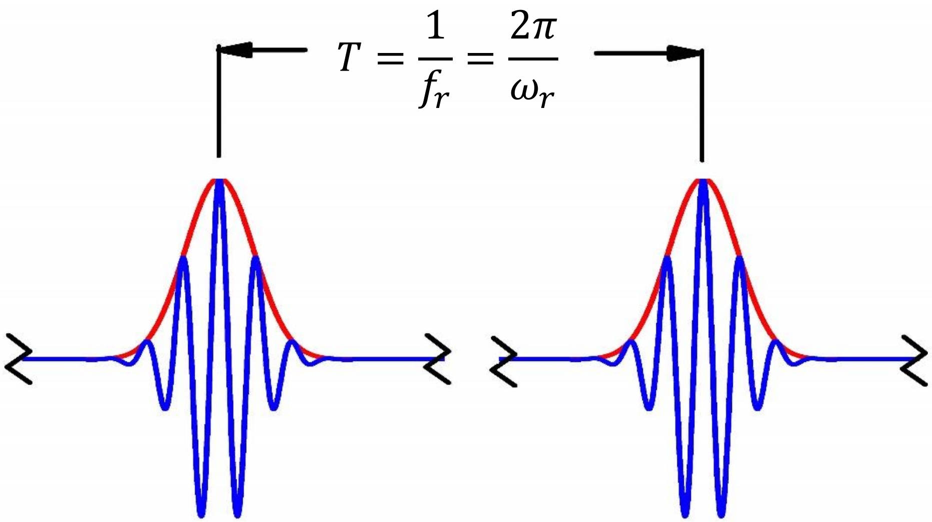


$$E_p(t) \leftrightarrow \tilde{E}_p(\omega)$$

Fourier transformation

a series of identical pulses

typical numbers:
$T \cong 10^{-9}\text{s}$, $\delta t \cong 10^{-14}\text{s}$

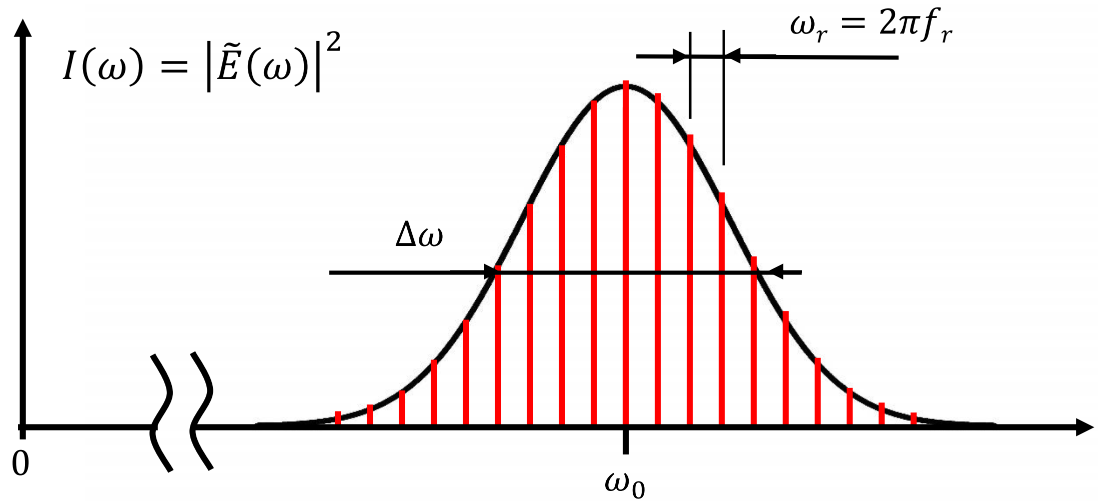


$$E(t) = \sum_{n=-\infty}^{n=\infty} E_p(t - nT)$$

Fourier transformation

$$\tilde{E}(\omega) = \tilde{E}_p(\omega) \sum_{n=-\infty}^{n=\infty} \delta(\omega - n\omega_r)$$

$$\omega_n = \omega - n\omega_r$$



ere the pulses from a fs oscillator identical?

ideal laser, no vibrations, no other sources of noise

$$E_n(t) = A(t)e^{i\omega_0 t}$$

$$E_{n+1}(t) = A(t-T)e^{i\{\omega_0(t-T)+\Delta\varphi\}}$$

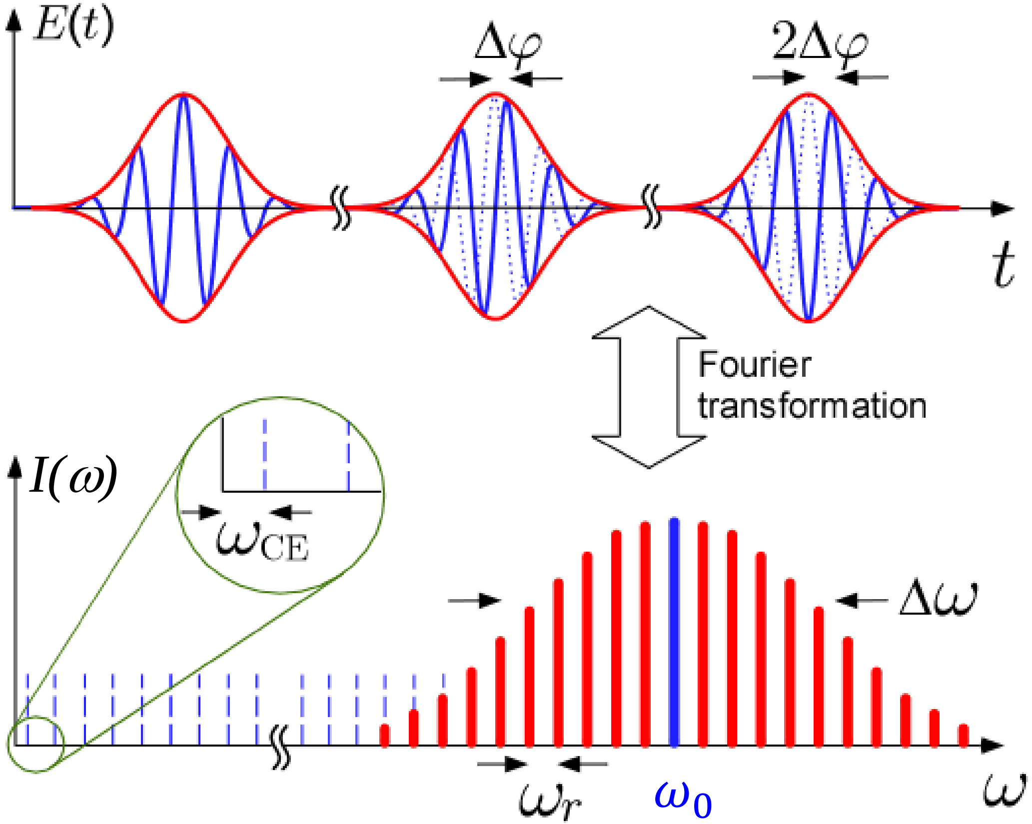
$$T = {}^{L}/_{v_g}, \Delta\varphi = \omega_0\left(\frac{L}{v_g} - \frac{L}{v_p}\right)\mathrm{mod}2\pi$$

v_g - group velocity

v_p - phase velocity

if $\Delta\varphi \neq 0$ then we have a constant phase shift between two consecutive pulses

the consequences of phase shift



$$\omega_n = n\omega_r + \omega_{CE}$$

$$\tilde{E}(\omega) = \tilde{E}_p(\omega)\sum_{n=-\infty}^{n=\infty}\delta(\omega - n\omega_r - \omega_{CE})$$

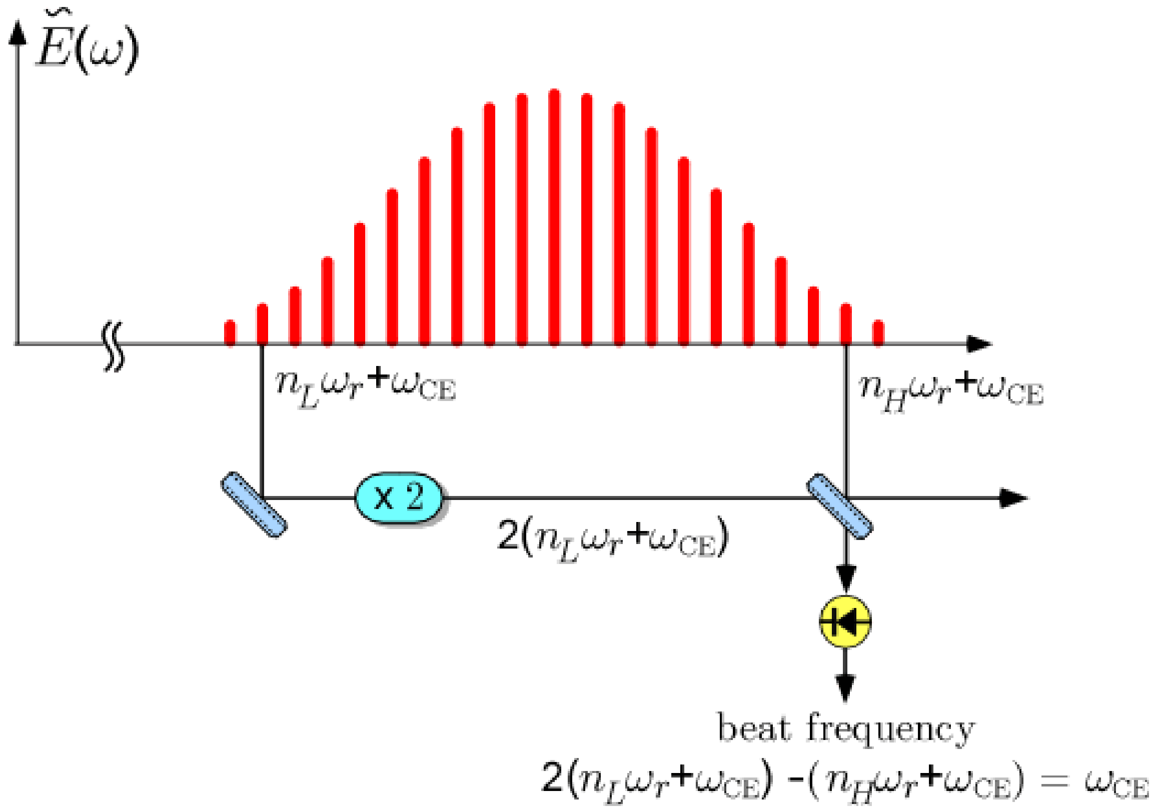
$$\omega_{CE} = \frac{\Delta\varphi}{2\pi}\omega_r$$

$f_r = \frac{\omega_r}{2\pi}$ - laser repetition rate is easy to measure, all we need is a photodiode and an electronic counter

$f_{CE} = \frac{\omega_{CE}}{2\pi}$ determination is not simple

f-2f method for f_{CE} detrmination

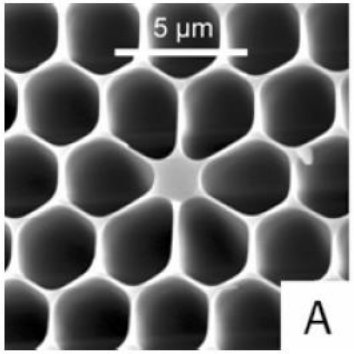
idea



? frequency doubling

? octave spanning spectrum

spectral broadening

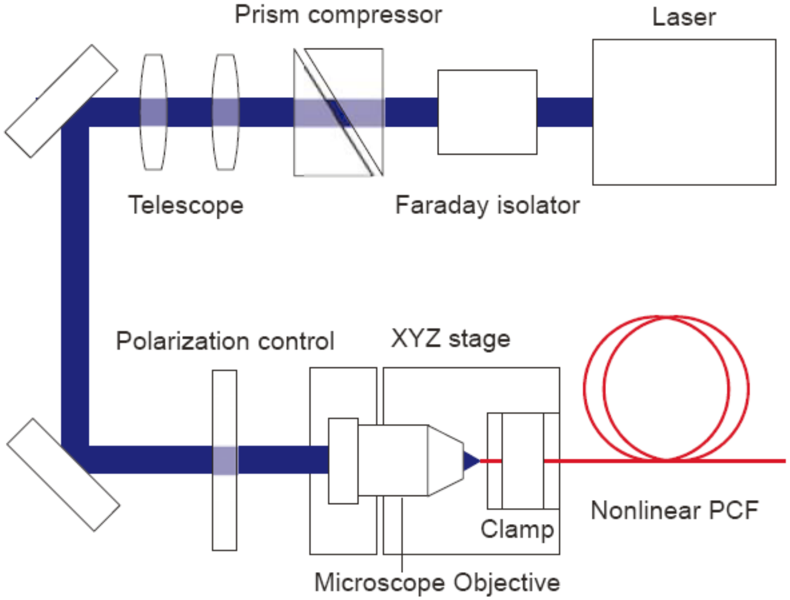


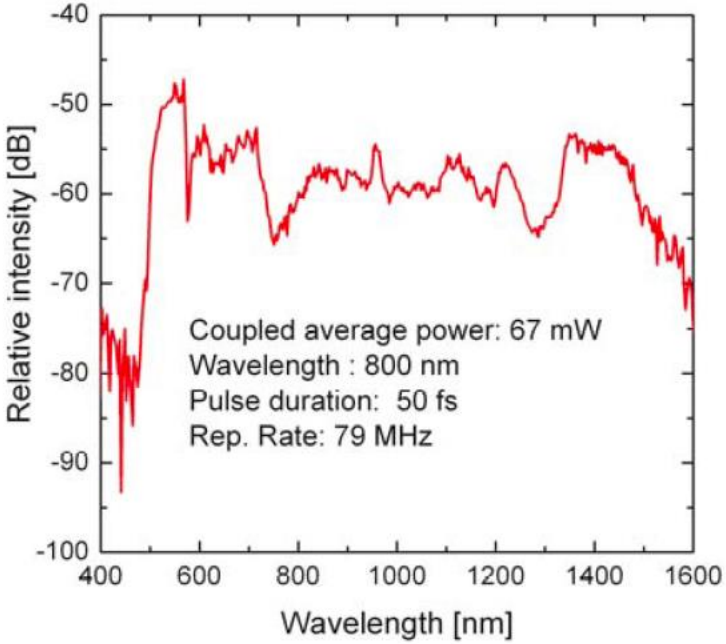
photonic crystal fiber:

- zero dispersion
- small core

4-wave mixing

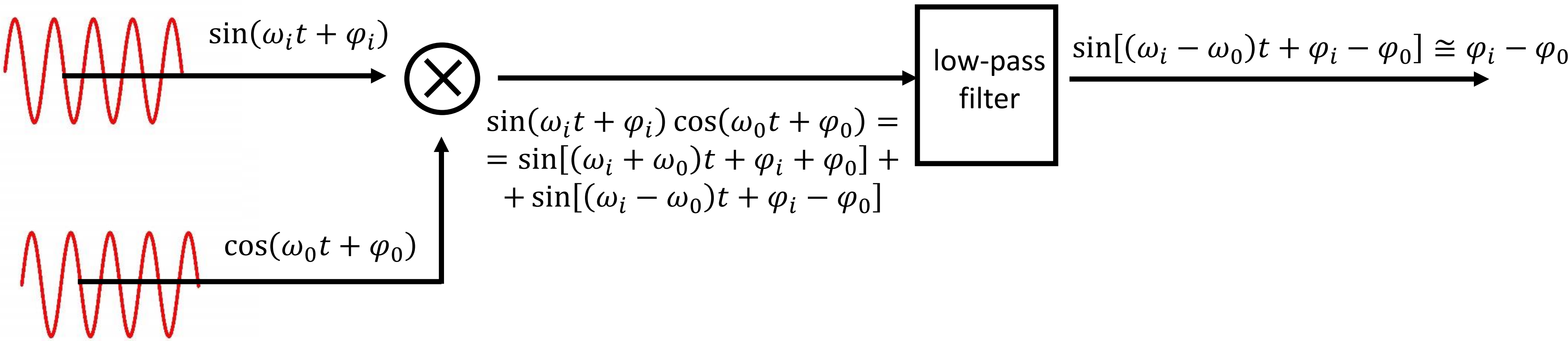
$$\omega = \omega_1 + \omega_2 - \omega_3$$
$$= (n_1 + n_2 - n_3)\omega_r + \omega_{CE}$$



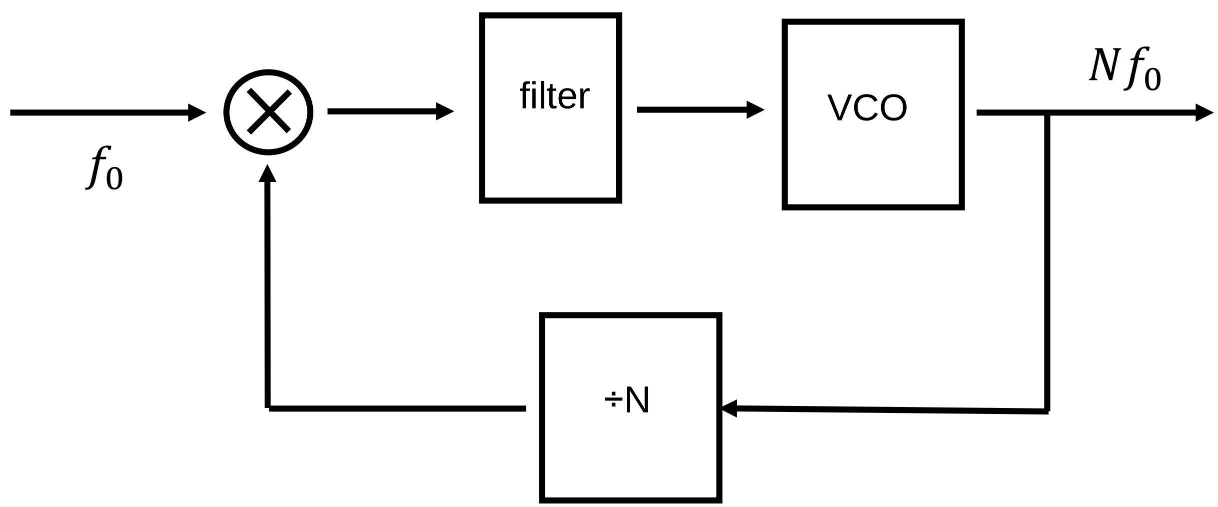


phase locked loop (PLL)

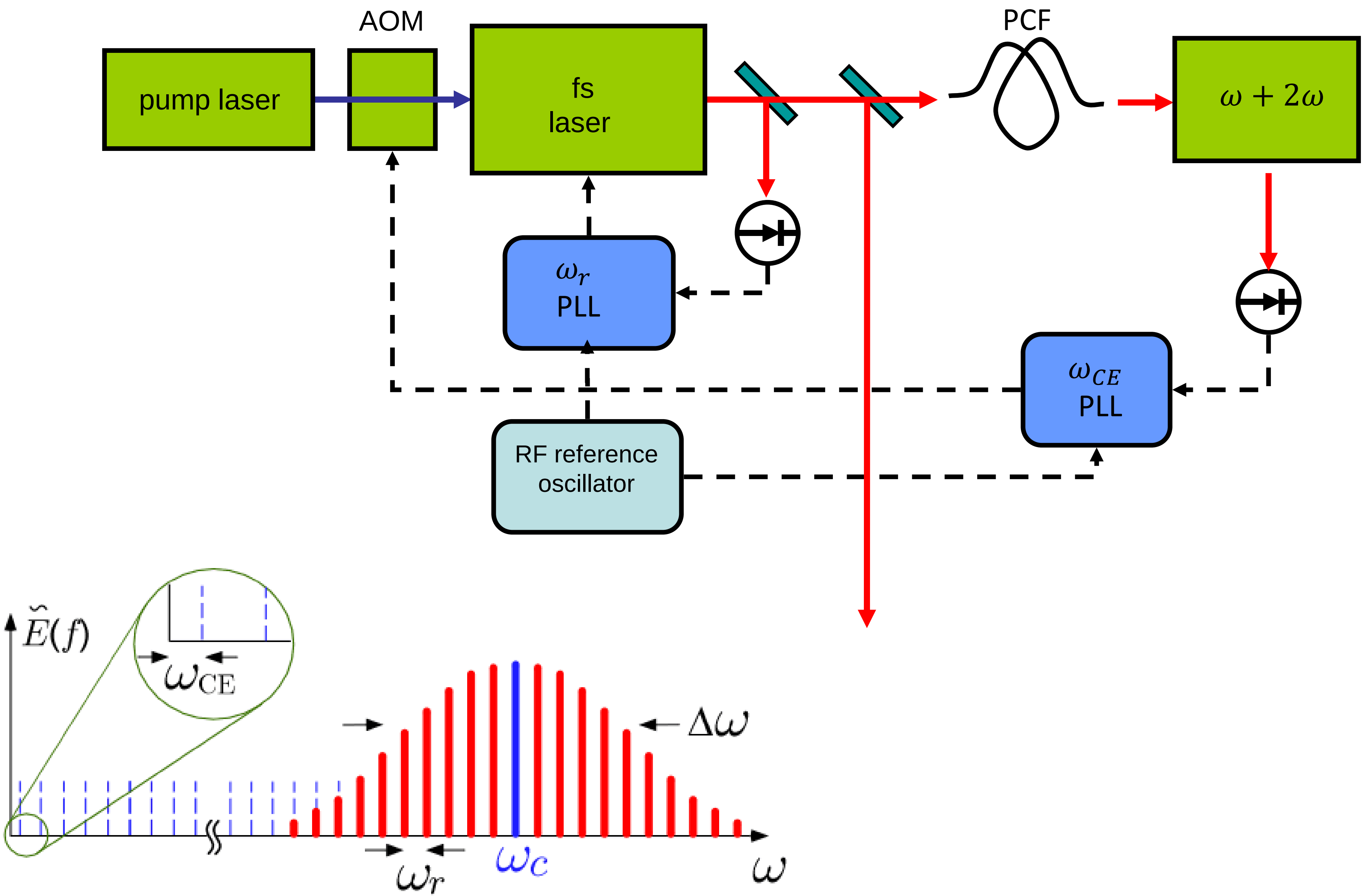
phase detector



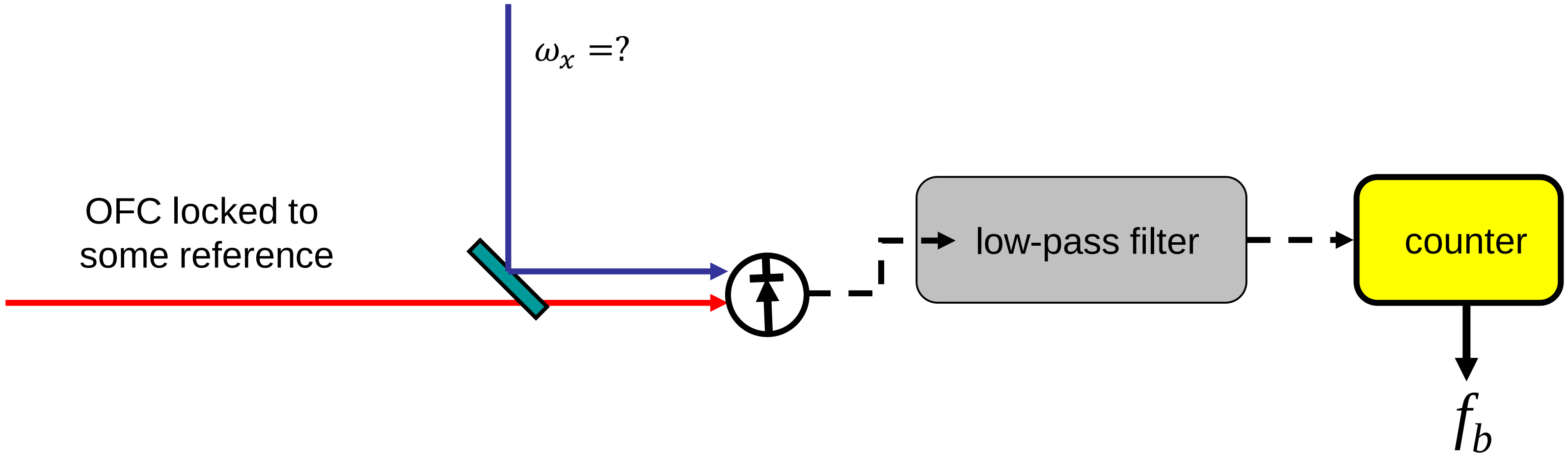
application example: electronics frequency multiplier

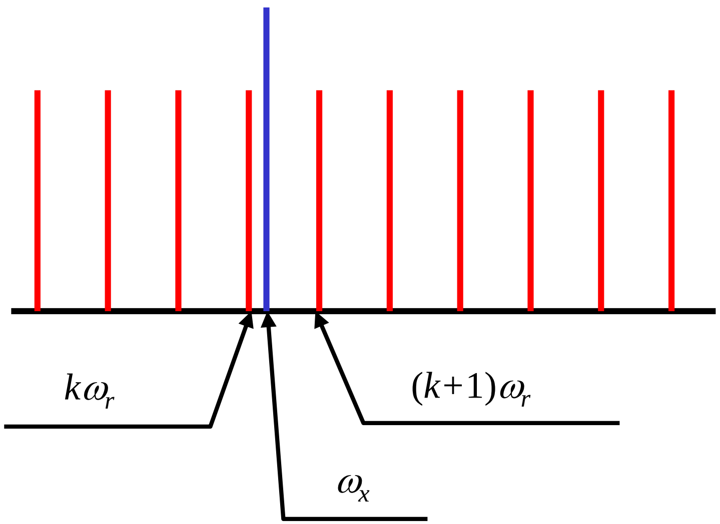


OFC locked to RF reference



we can measure laser frequency





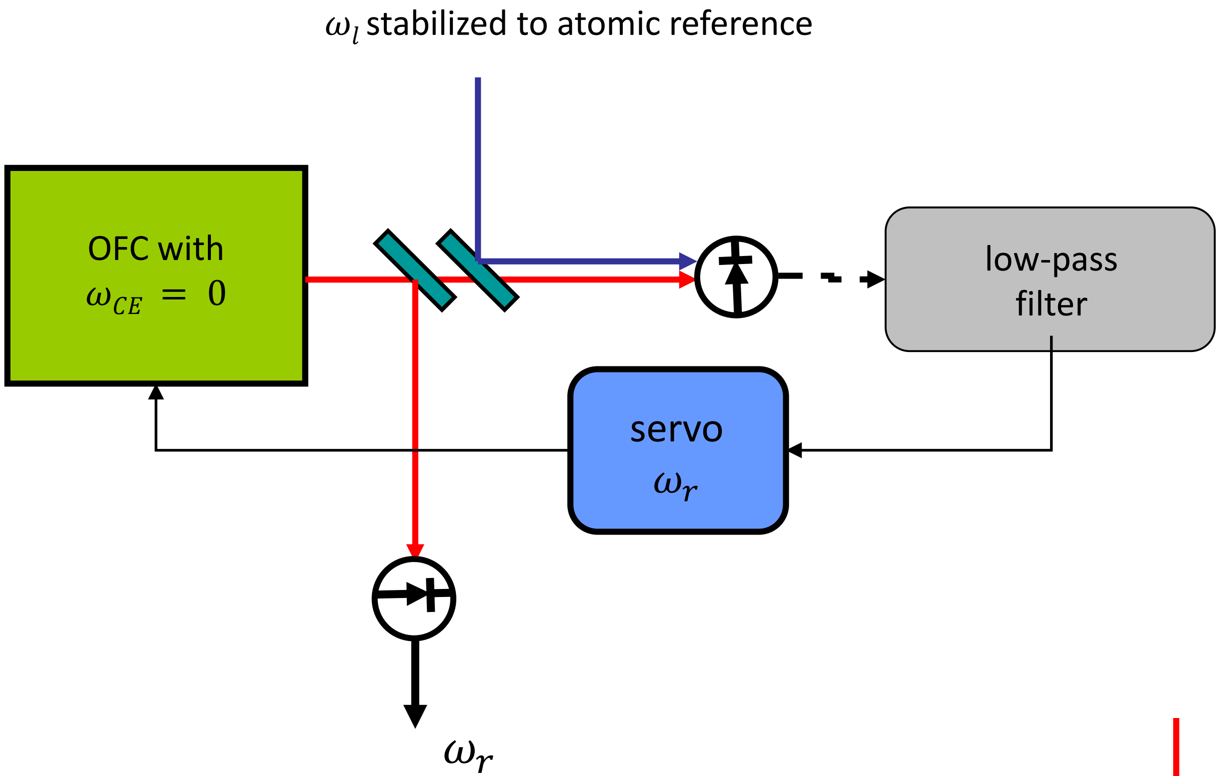
$$f_b = \frac{|n\omega_r - \omega_x|}{2\pi}$$

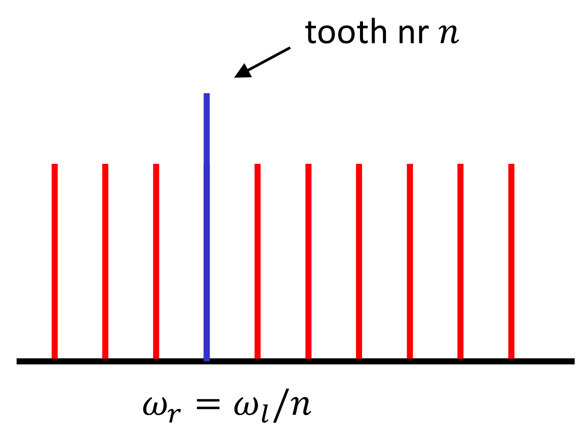
$n = ?$

if we can determine n then

$$\omega_x = n\omega_r \pm 2\pi f_b$$

optical atomic clock





$$\sigma(\tau) = \left\langle \frac{\Delta \nu_{rms}}{\nu_0} \right\rangle_\tau \approx \frac{\Delta \nu}{\pi \nu_0} \sqrt{\frac{T}{\tau N}}$$

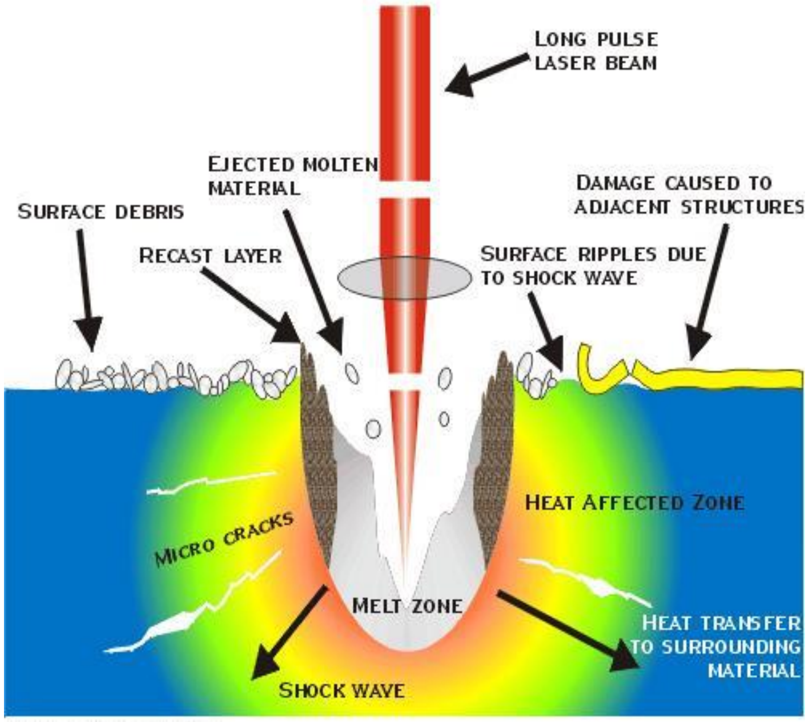
laser (micro)machining and fabrication

machining methods comparison

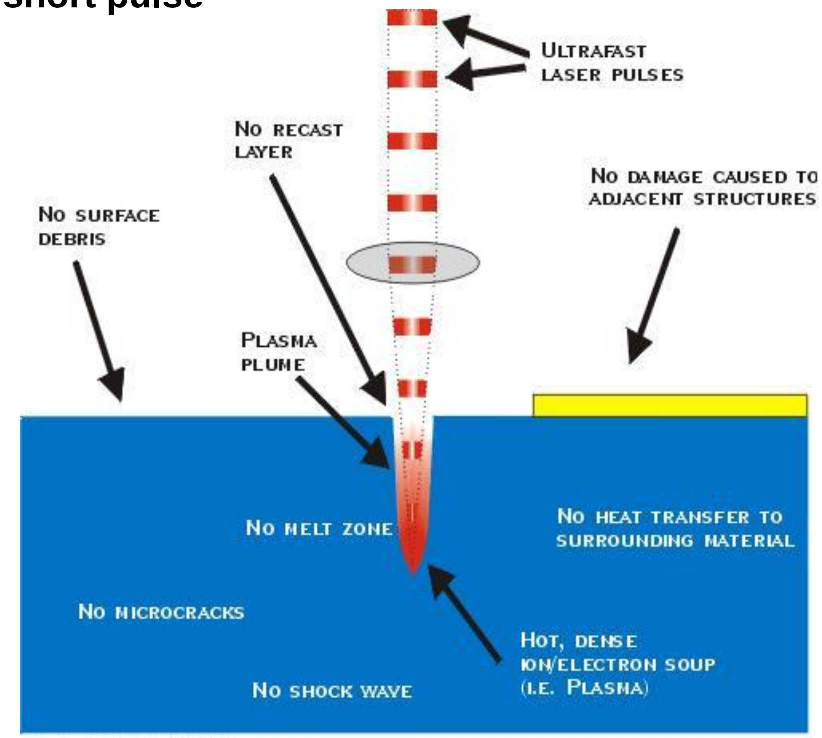
Process	Resolution μm	Surface Roughness μm	Side Effects
Mechanical	100	6.3-1.6	Burring, requires polishing
EDM	100	4.75-1.6	Electrode wear, rough finish, slow and unclean process
Chemical Etch	250	6.3-1.6	Undercutting
LIGA	5	1-2	Synchrotron source: very expensive
Nd: YAG Laser	50	1	Redeposition
Excimer Laser	5	> 1 μm (nm range)	Recast Layer, aspect ratios
Ti:sapphire Ultrafast Laser	< 1	nm range	Higher power ranges may require vacuum environment

long vs short pulse micromachining

long pulse

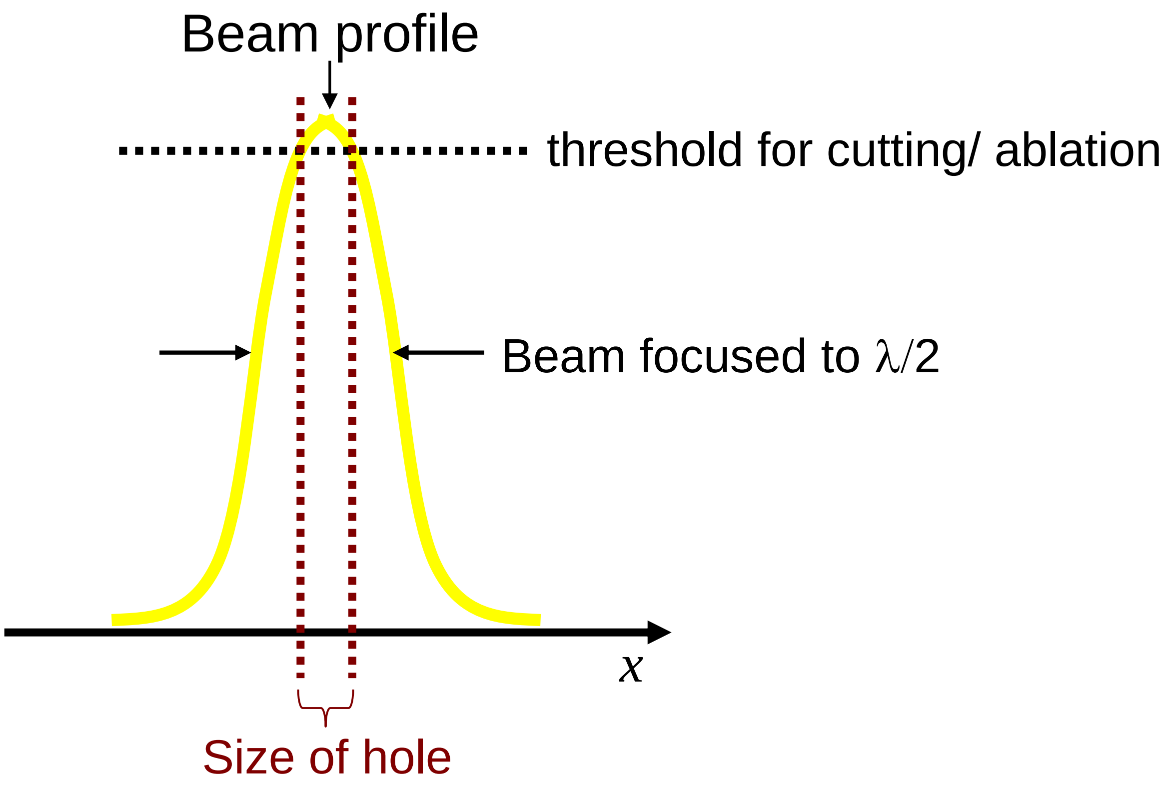


short pulse



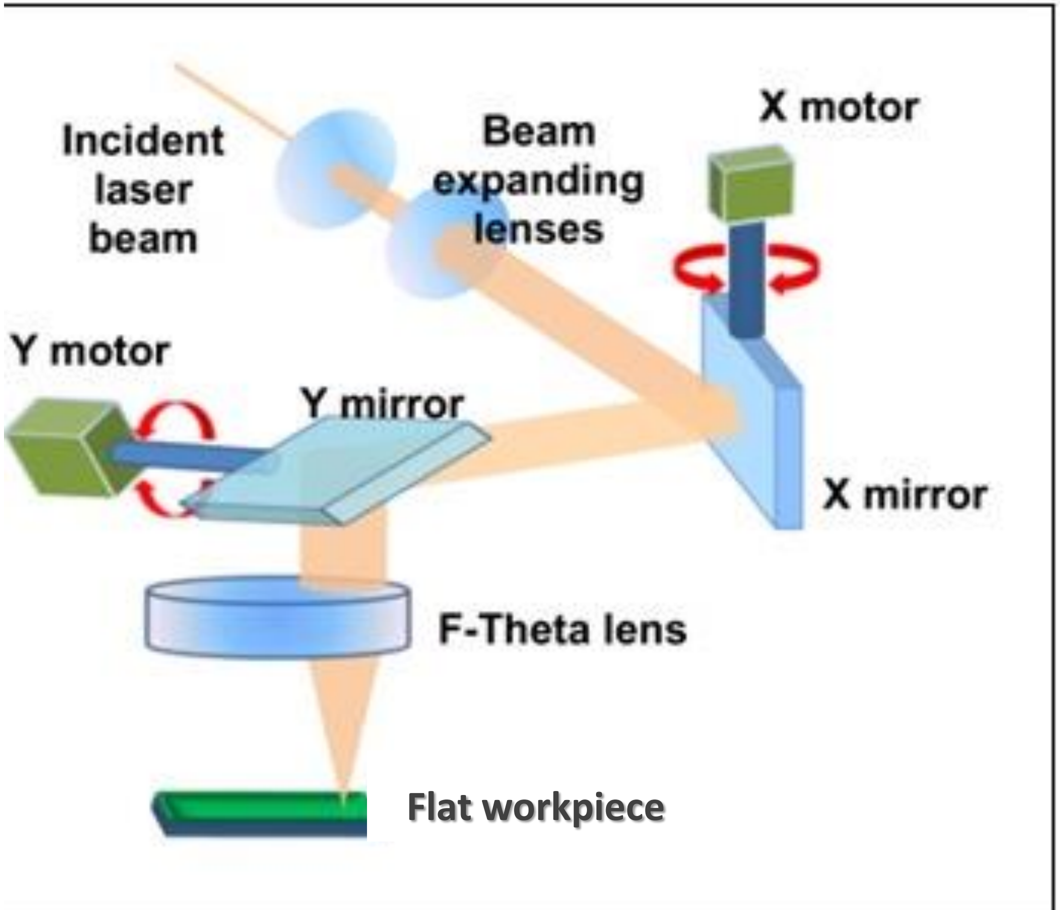
The main **advantages** of femtosecond micro machining:
- no thermal damage: high machining quality, heat sensitive material machining possible
- unmatched accuracy: down to 100nm (very well defined ablation threshold)
- no wavelength dependence: any material can be machined with the same laser

threshold effect in laser micromachining



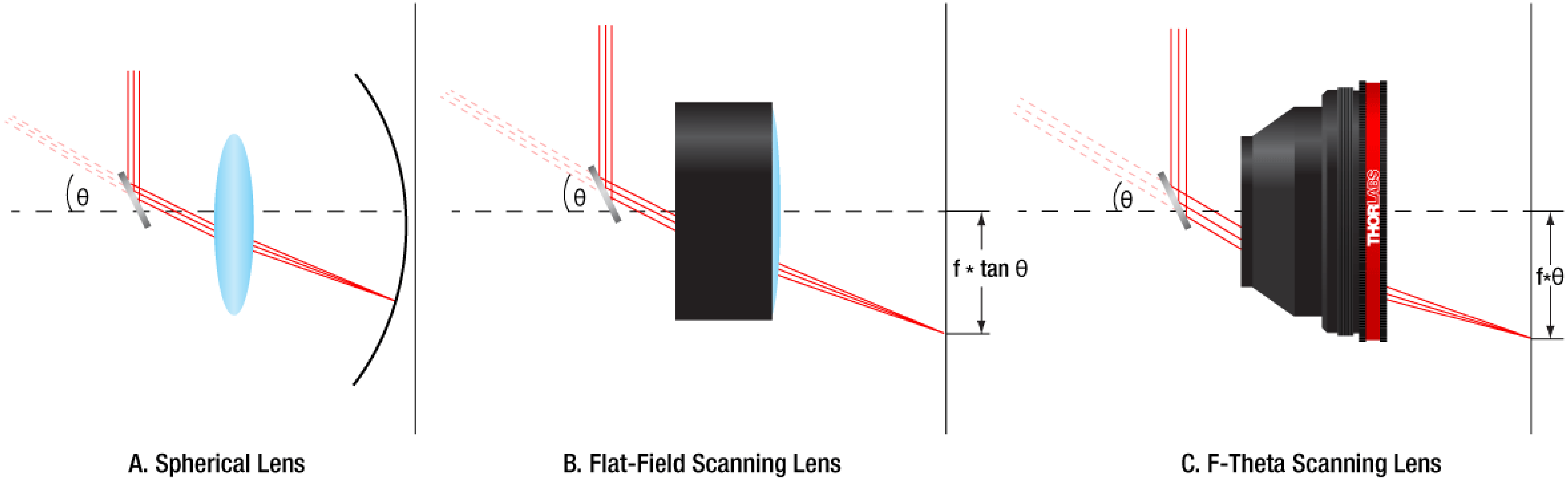
Because high-order nonlinear-optical processes are responsible for cutting, there is effectively a threshold for cutting. This means that careful control of the intensity can yield a hole with the diameter smaller than the laser beam diameter

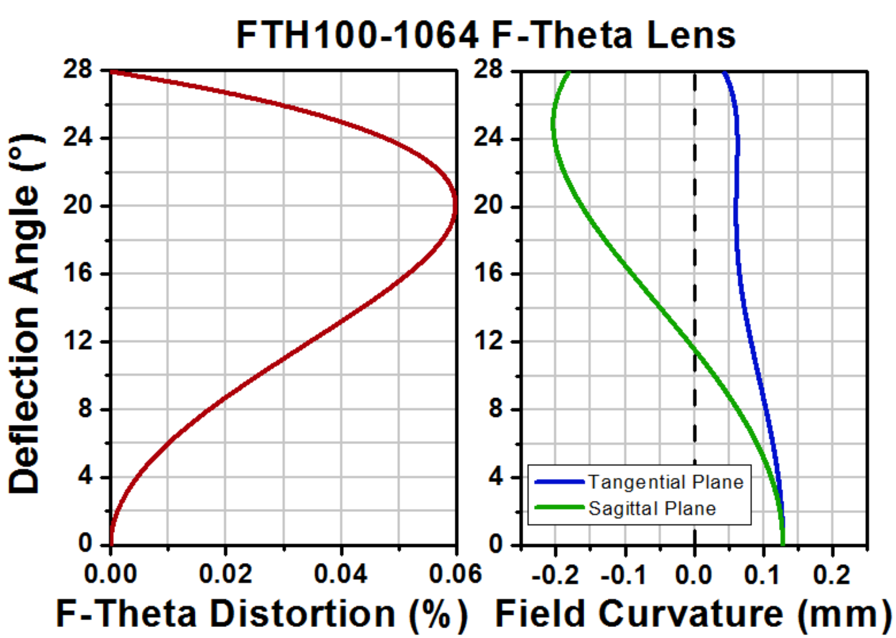
laser micromachining system architecture for a flat work area



- laser
- routing optics (stability)
- beam size control (focus size)
- focal plane position control
- galvo-scanner (kHz rate scanning)
- f – theta lens
- flat workpiece

F - theta lens





source: Thorlabs

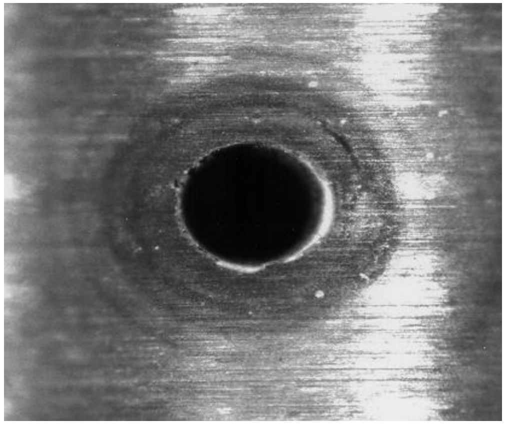
advantages, features

advantages of picosecond/femtosecond laser micromachining:

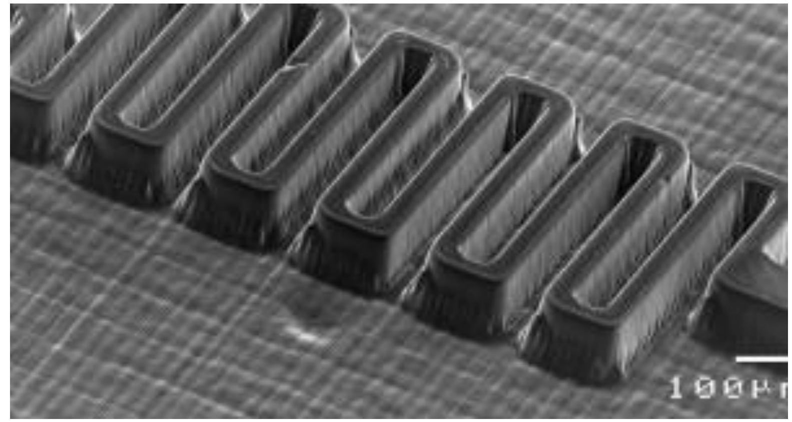
- Non-contact
- No pre/post processing of material
- Wide range of materials: fragile, ultra-thin and highly reflective surfaces
- Process can be fully automated
- Very high peak powers in the range $10^{13} W/cm^2$ provide for minimal thermal damage to surroundings
- Very clean cuts with high aspect ratios
- Sub-micron feature resolution
- Possible to machine transparent materials like glass, sapphire etc

examples of ps/fs micromachining

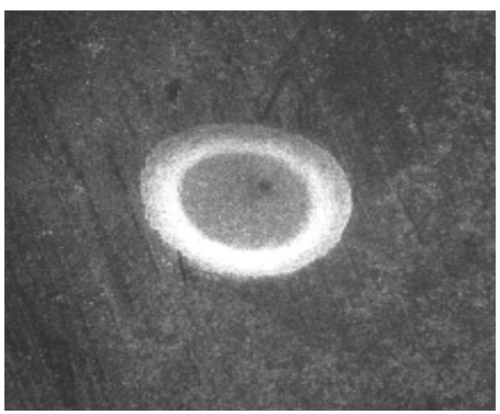
Ceramics



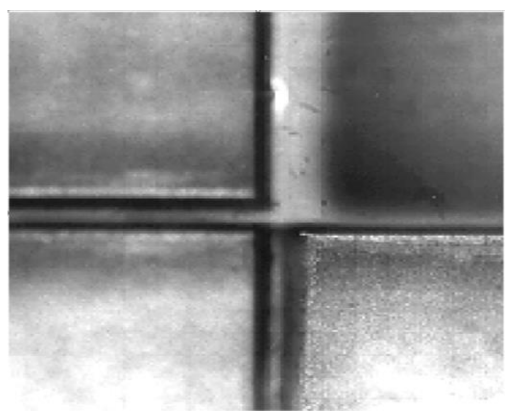
Diamond



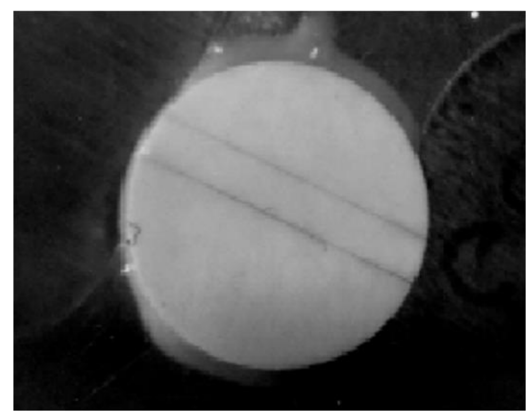
Teeth



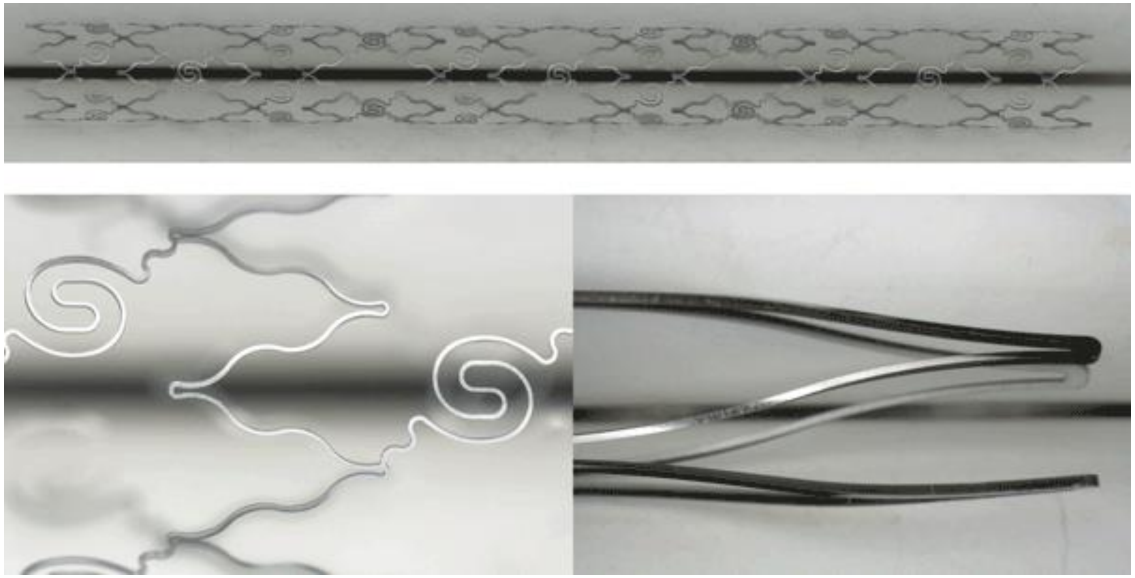
Polymers



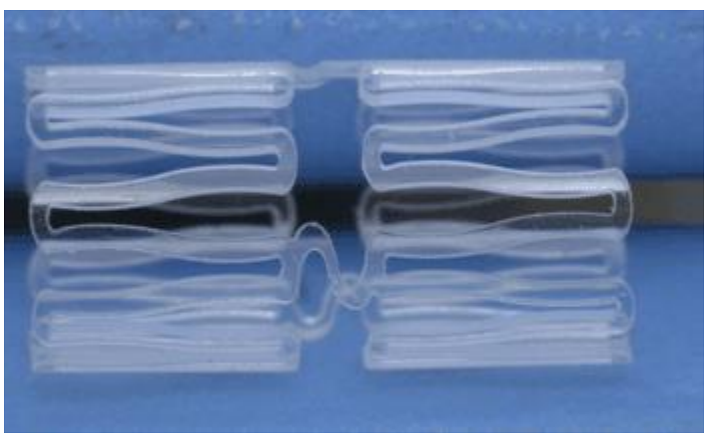
High Explosives



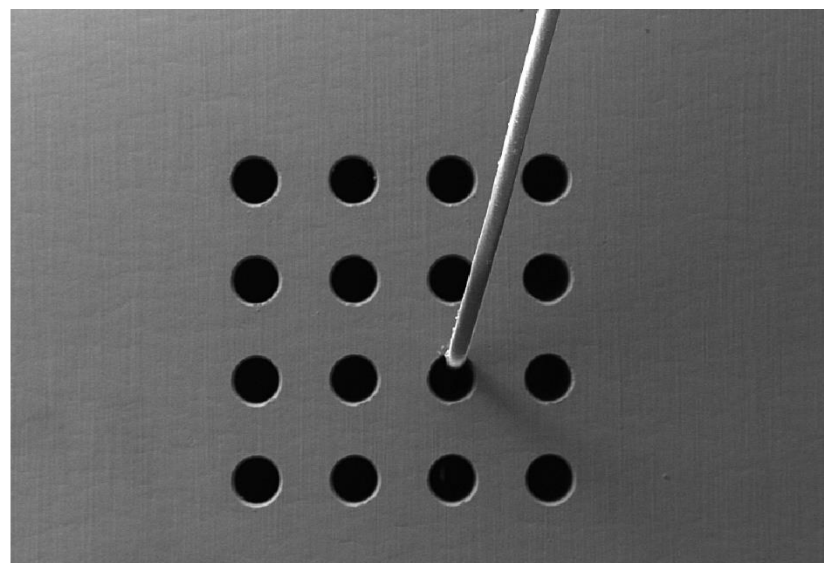
more examples



nitinol stent – ps laser, tube diameter 4.25 mm, wall thicknes 45μm

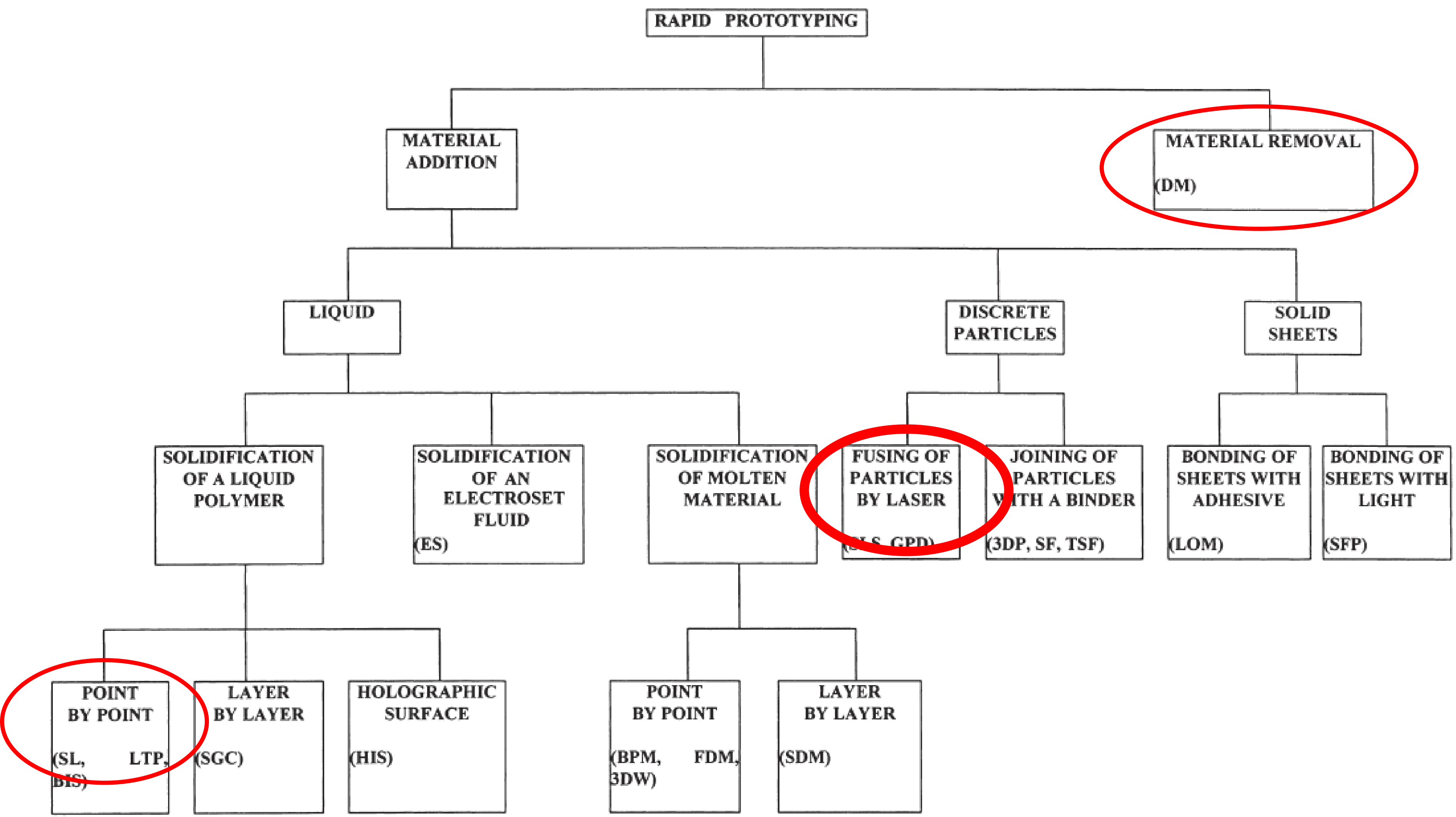


bio-absorbable poly-L-lactic acid (PLLA)
machined by femtosecond laser pulses

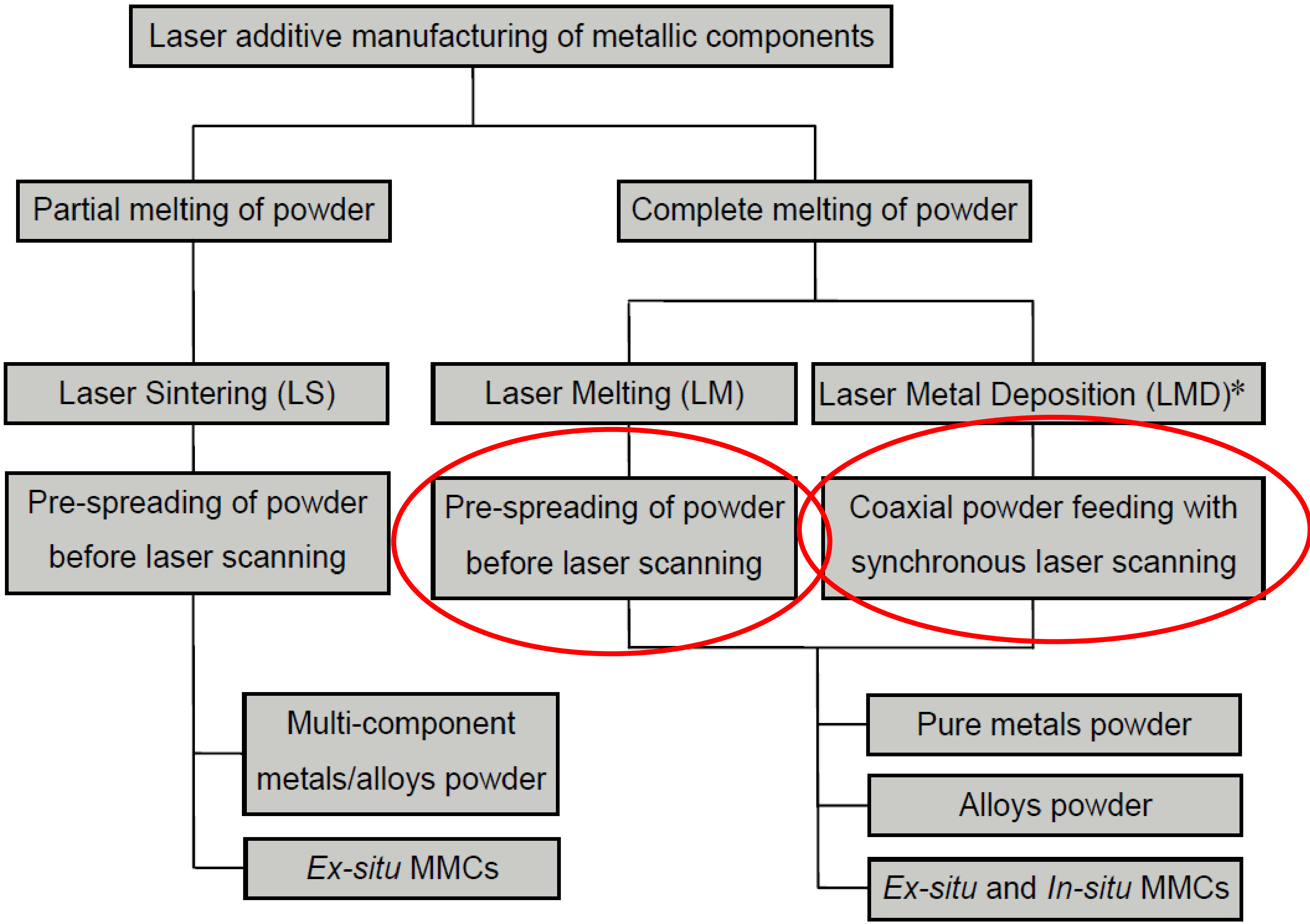


stainless steel foil, hole diameter 100μm

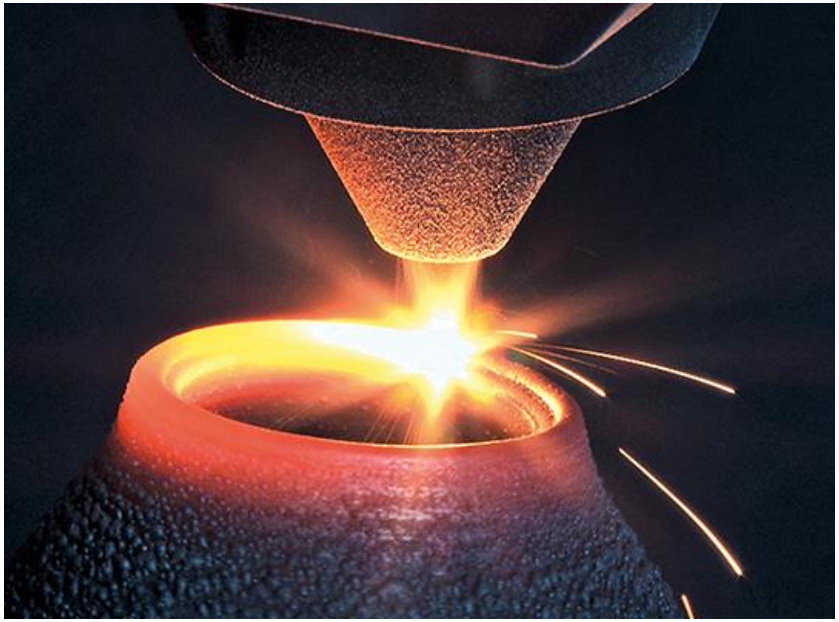
rapid prototyping/manufacturing



laser additive manufacturing, 1



laser additive manufacturing, 2

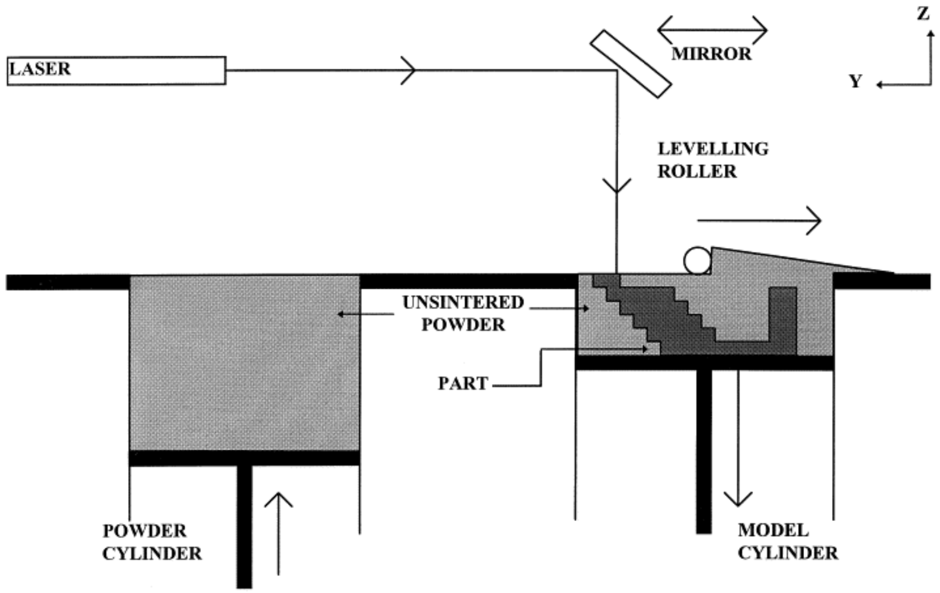


coaxial metal powder feeding

applications:

- parts regeneration
- manufacturing of complex shapes, especially hollow parts

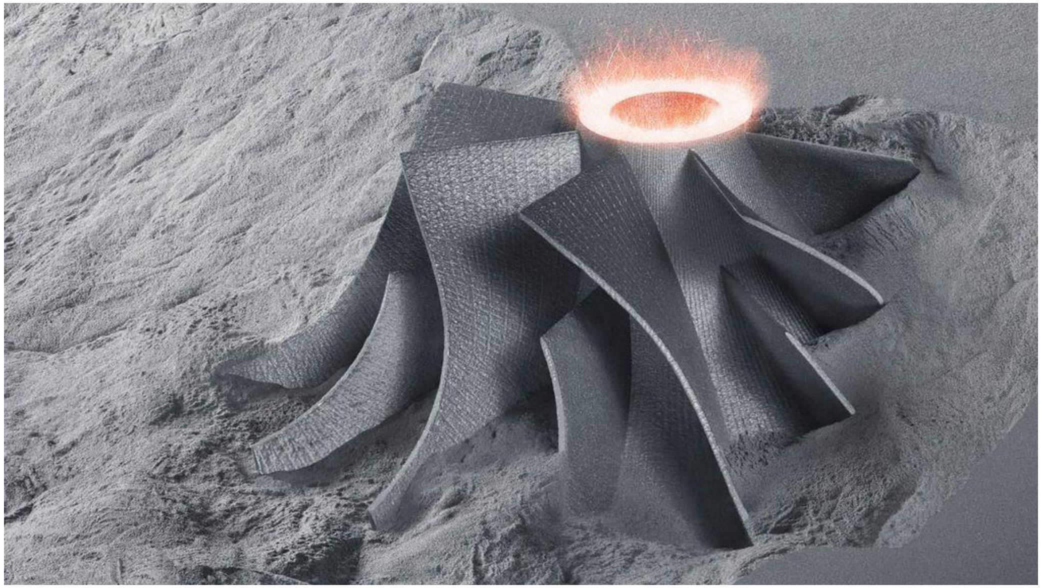
laser additive manufacturing, 3



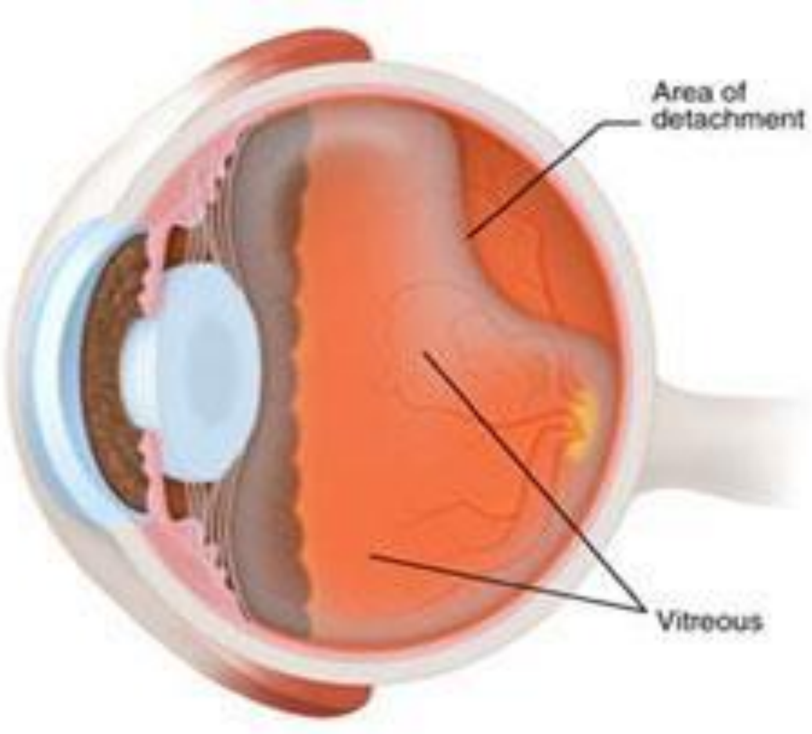
powder spreading

applications:

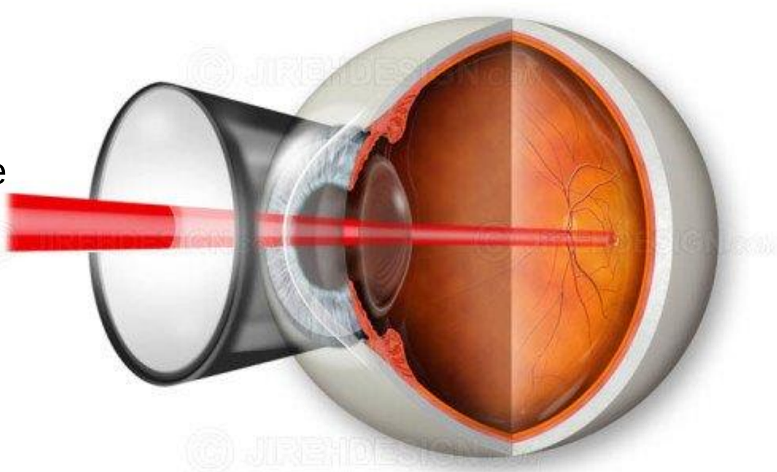
- rapid prototyping
- manufacturing of complex metallic shapes

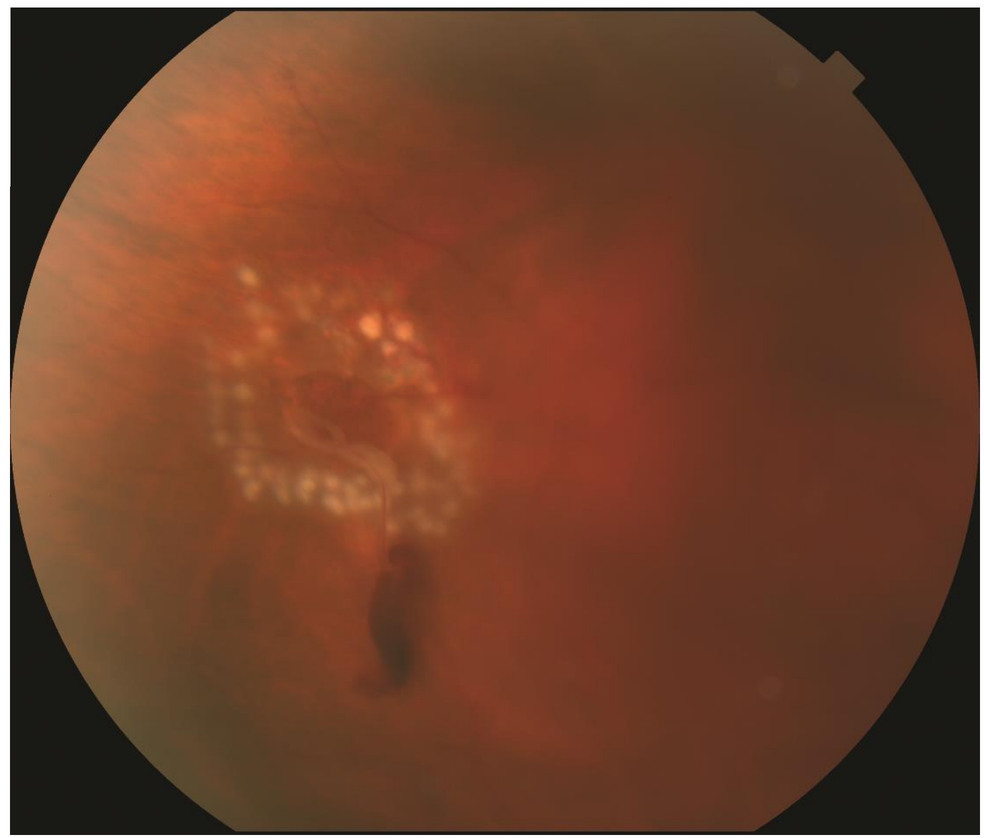


retinal laser surgery



visible
laser
beam

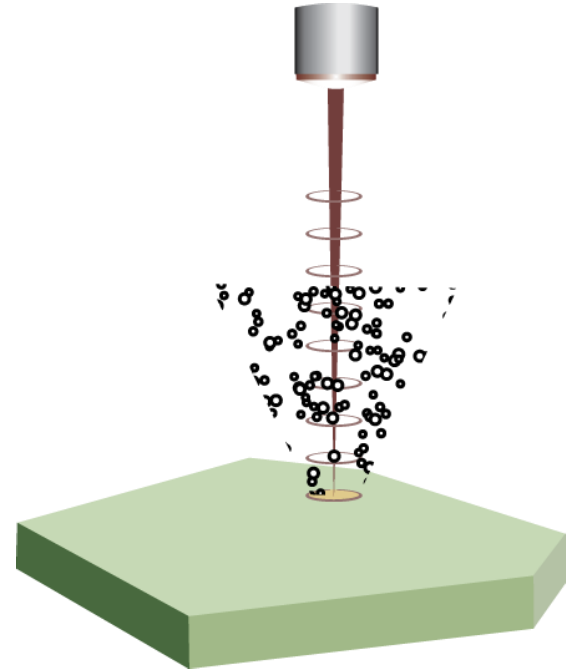




excimer laser ablation

excimer lasers

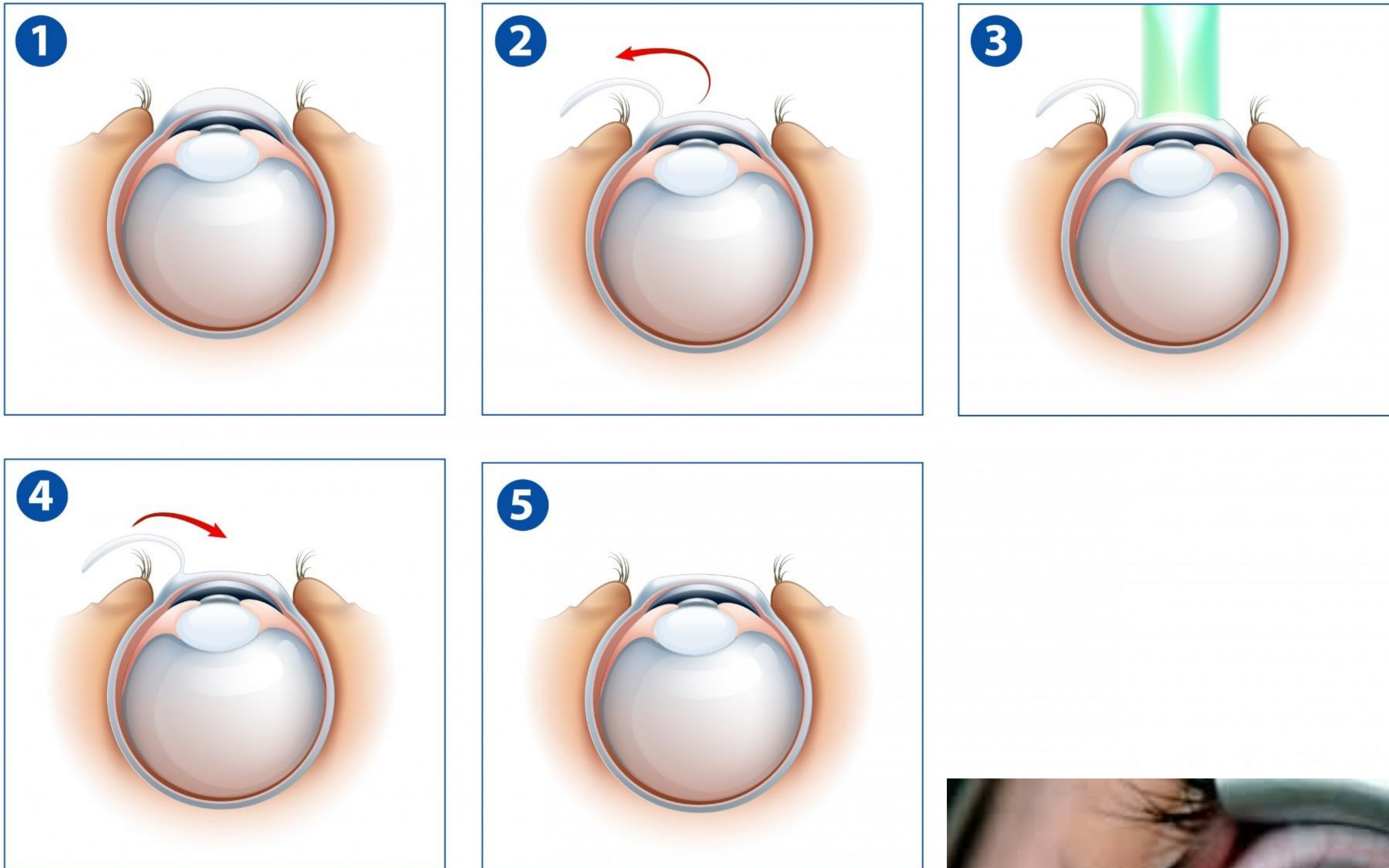
excimer	wavelength
F_2 (fluorine)	157 nm
ArF (argon fluoride)	193 nm
KrF (krypton fluoride)	248 nm
XeBr (xenon bromide)	282 nm
XeCl (xenon chloride)	308 nm
XeF (xenon fluoride)	351 nm



UV ablation of organic materials:

- penetration depth – a few micrometers
- physical effect of UV photon absorption – breaking chemical bond
- no debris – photodissociated products are in gas form
- negligible thermal effects

Laser-Assisted in situ Keratomileusis (LASIK)



more of laser cleaning

Professional teeth cleaning and laser
removal for dark gum pigmentation.

cleaning of art with laser beam, 1

cleaning of art with laser beam, 2