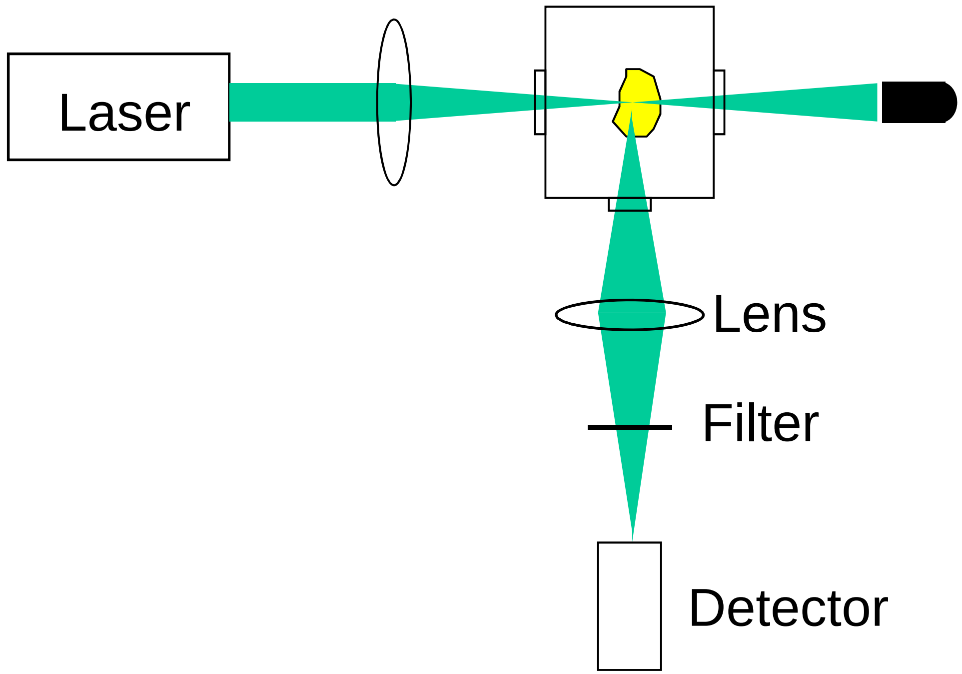
3. Instrumentation for optical combustion diagnostics

Equipment for combustion laser diagnostics

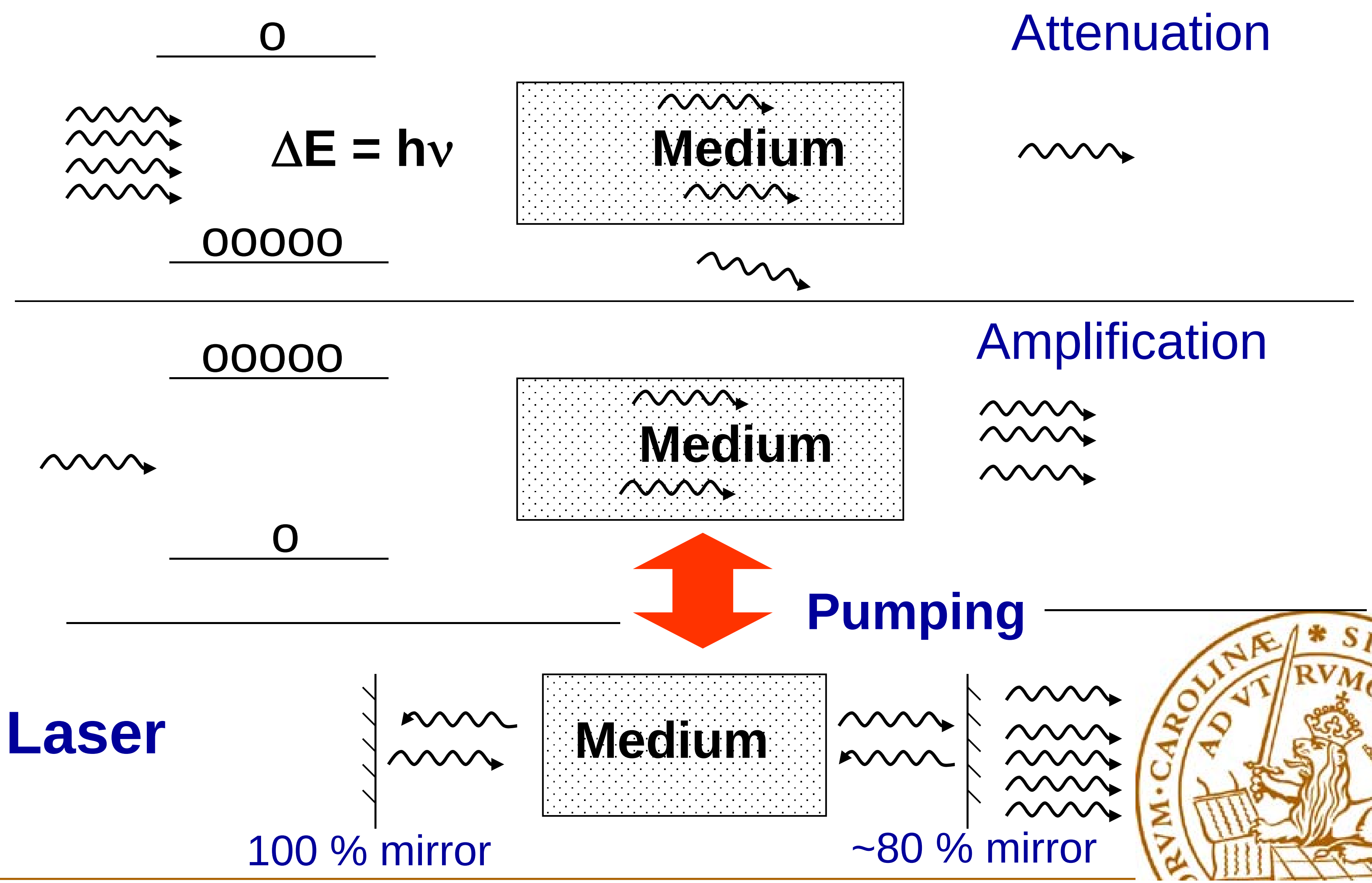
1) **Laser/Laser system**
2) **Optics**
   - Lenses
   - Polarizer
   - Filters
   - Mirrors
   - Etc.
3) **Detector**
   - CCD-camera
   - Spectrometer + CCD-camera
   - Photomultiplier + Digital oscilloscope
   - Etc.



General experimental setup for laser diagnostics

Laser

Light **A**mplification by **S**timulated **E**mission of **R**adiation



Laser characteristics

- Lasers are nearly monochromatic (< 1 cm^{-1})
- Lasers are coherent (in phase)
- Lasers can be tunable (continuous wavelength tuning)
- Lasers are highly directional (laserbeam)
- Lasers can be CW or pulsed (ns, fs, as!)
- Lasers can give very high laser pulses (J)

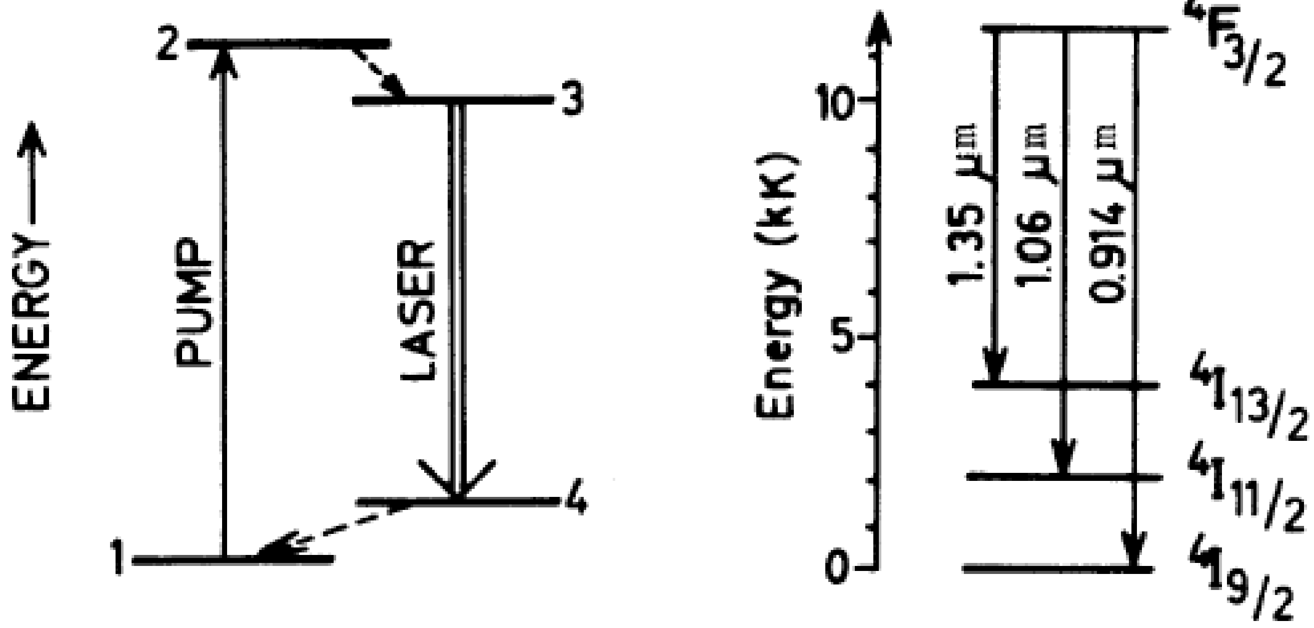
Laser safety

- When working (or visiting) in laboratories with lasers it is very important to have knowledge in laser safety.
- Some lasers give radiation in the ultraviolet and infrared regions that can not be seen by the eye.
- Direct laser radiation but also reflexes from optics and surfaces can give serious damage to an eye**.**
- IMPORTANT! No person should take part in any experiment without having a guide and relevant protection glasses

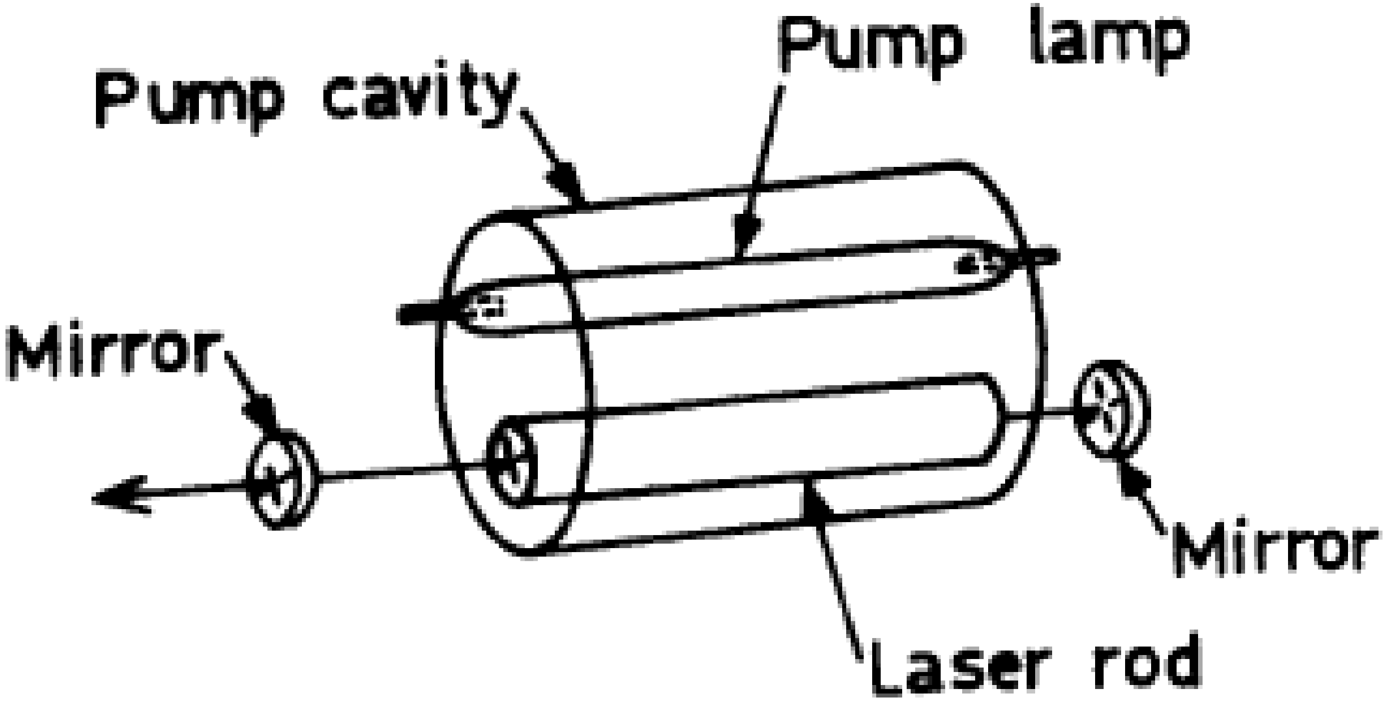
Laser survey

1. Nd:YAG laser
2. Excimer laser
3. (Argon-ion laser)
4. Dye-laser
5. Multi-YAG laser

Nd:YAG laser: Energy level diagram



Principle for the YAG laser



Nd:YAG laser

Typical specification:

- Pulselength: ~5-10 ns
- Wavelenght: 1.06 μm, 532 nm, 355 nm, 266 nm
- Pulse energy @ 532 nm, 500mJ -1J
- Repetition rate: 10-20 Hz
- Linewidth: ~ 0.7 cm^{-1}, 0.1 cm^{-1}(etalon) 0.005 cm^{-1} (single mode)

Companies: e.g - Quantel, Continuum, Spectra Physics, Thales

Nd:YAG laser

Typical applications:

- Pumping a dye laser $\rightarrow$ all applications
- Raman scattering (532, 355, 266 nm)
- Laser-Induced Incandescence (532nm, 1.06 μm)
- Laser-induced fluorescence (266 nm)

Excimer laser

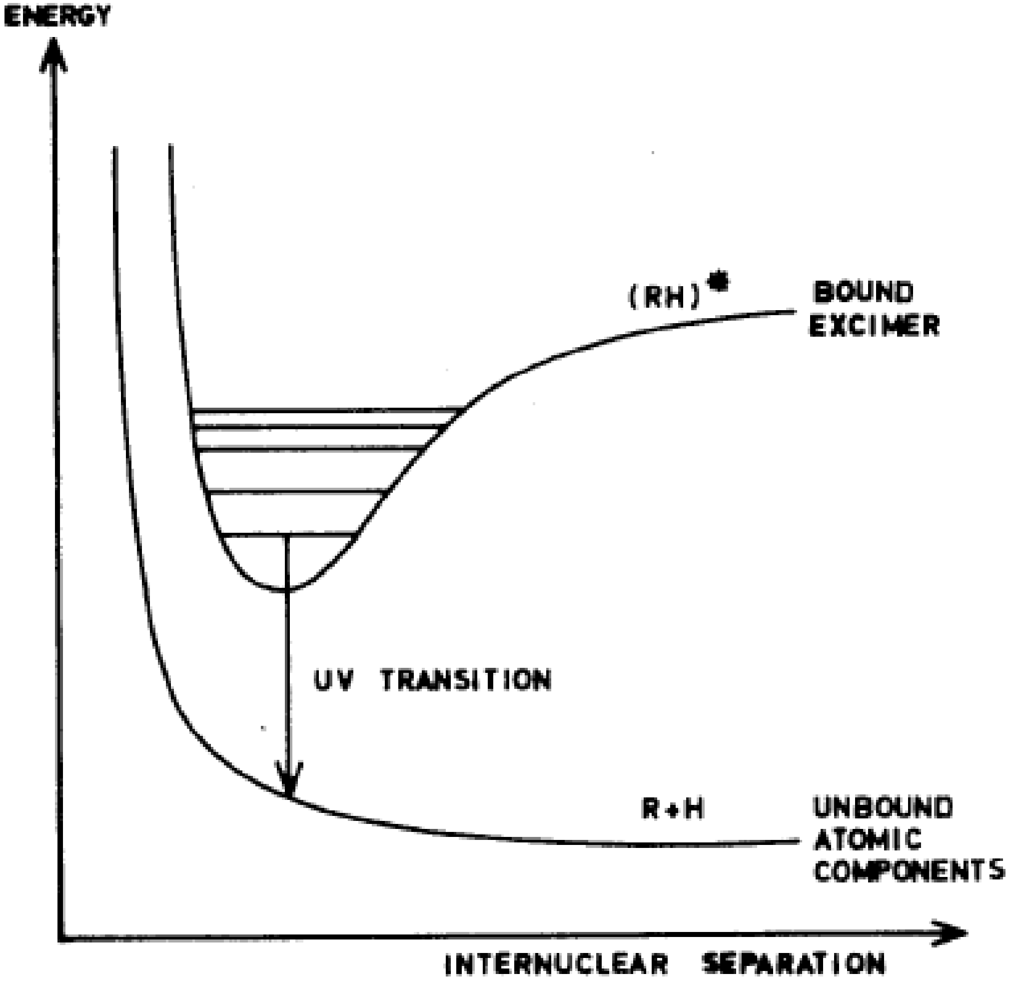


Table 1 . Different excimer molecules and the corresponding laser wavelengths.

Lasing medium	Ar_2	Kr_2	F_2	Xe_2	ArF	KrCl	KrF	XeCl	XeF
Wavelength (nm)	126	146	157	172	193	222	249	308	351

Excimer laser

Typical specification:

- Pulselength; ~10-15 ns
- Wavelenght; 248 nm, 308 nm
- Pulse energy @ 248 nm, ~250 mJ
- Linewidth. 1 -10 cm^{-1}, tunability possible

Companies: e.g - Lambda Physik

Excimer laser

Typical applications:

- Pumping a dye laser $\rightarrow$ all applications
- Raman scattering (248 nm, tunable)
- LIF (248 nm) - OH, H_2O, O_2, fuel
- LIF (308 nm) – OH, fuel

Need for a new laser?

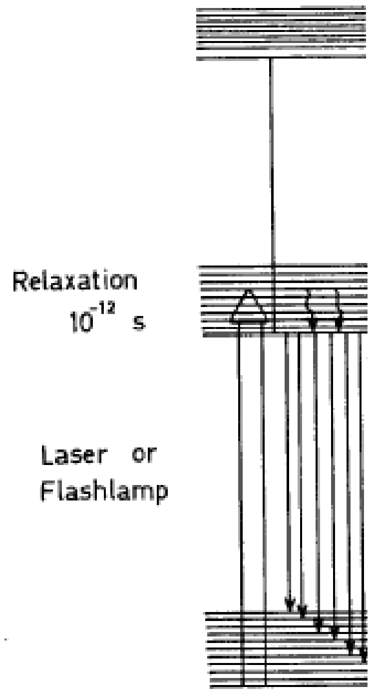
Specifications of an Alexandrite laser:

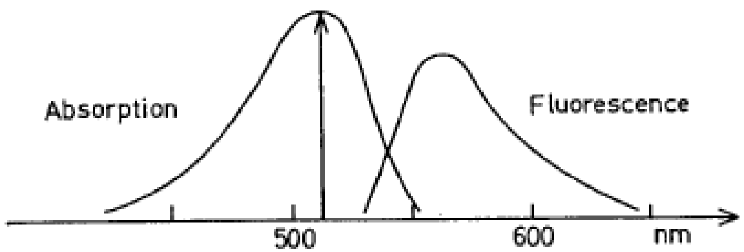
- Tunable (740-790 nm)
- High pulse energy: ~400 mJ (fundamental @ 776 nm) ~ 70 mJ @ 387, ~10 mJ @ 259 nm,
- Long pulse length: ~140 ns
- Single mode (~0.003 cm^{-1} linewidth)
- Multimode (~ 8 cm^{-1} linewidth)

Strong potential for CH visualization using the frequency doubled beam

Dye laser

In a dye laser the laser medium is a liquid, and the excitation source is a laser, often an Nd:YAG laser. A dye is chosen depending on the desired wavelength of the output from the laser.

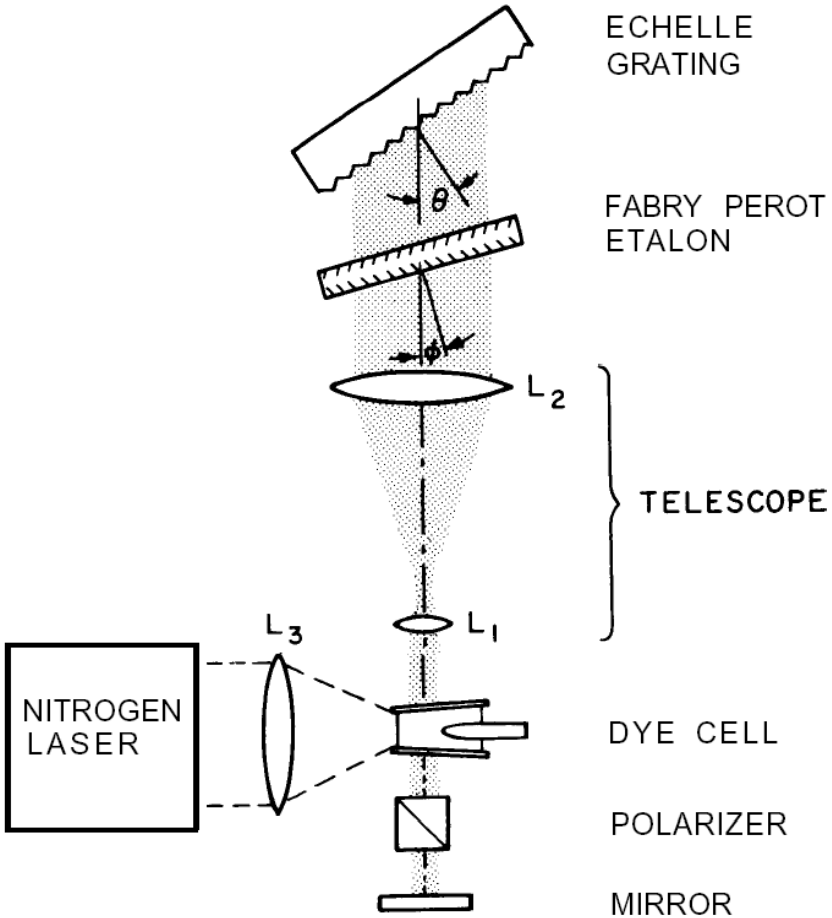




Dye laser

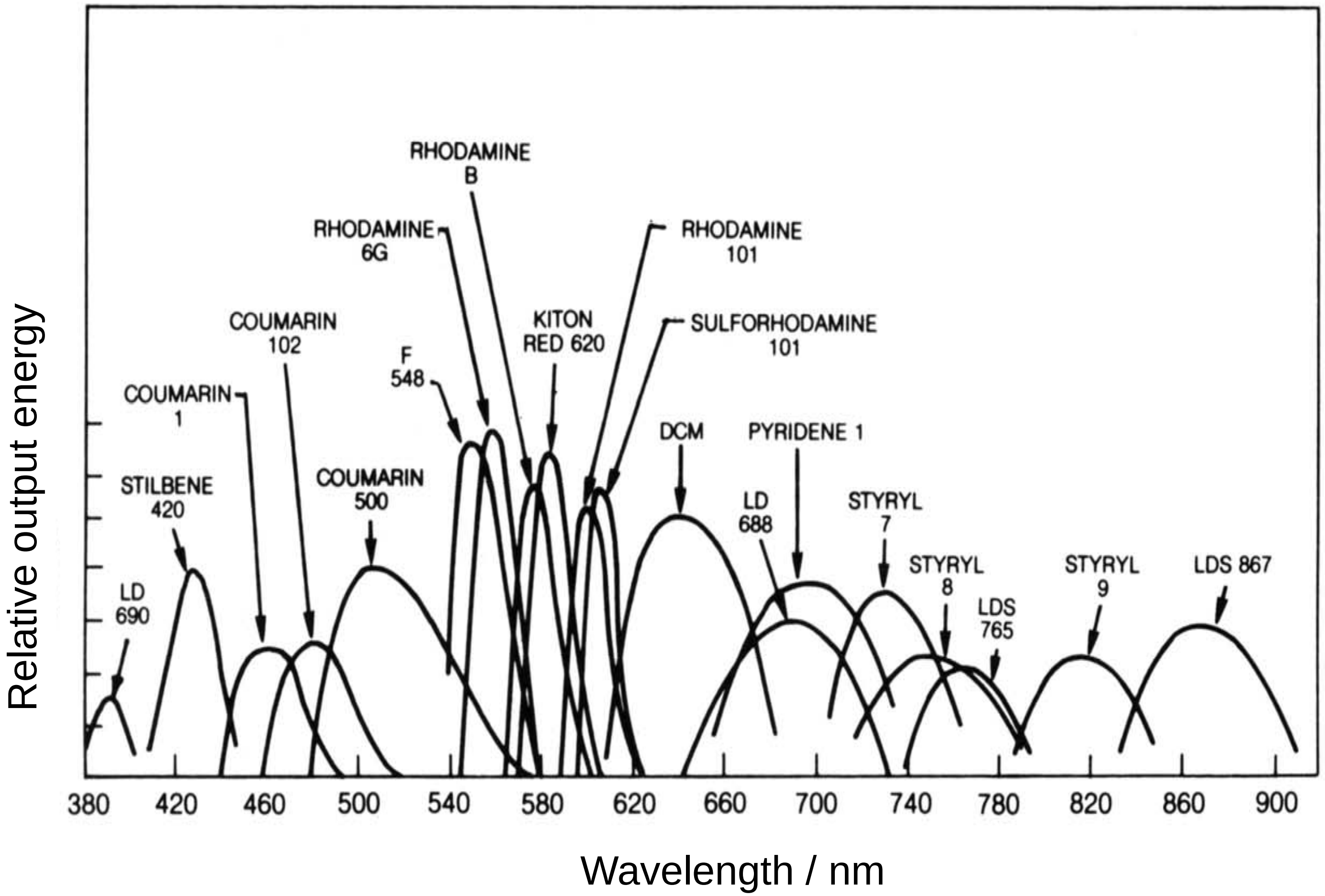
The dye laser can be operated in

- **narrowband mode** (typical linewidth ~0.3 cm^{-1}, and tuneable within the tuning range of the dye using a grating at the end of the cavity.
- **broadband mode** (typical linewidth ~150 cm^{-1} using an end mirror or a grating in zeroth order)



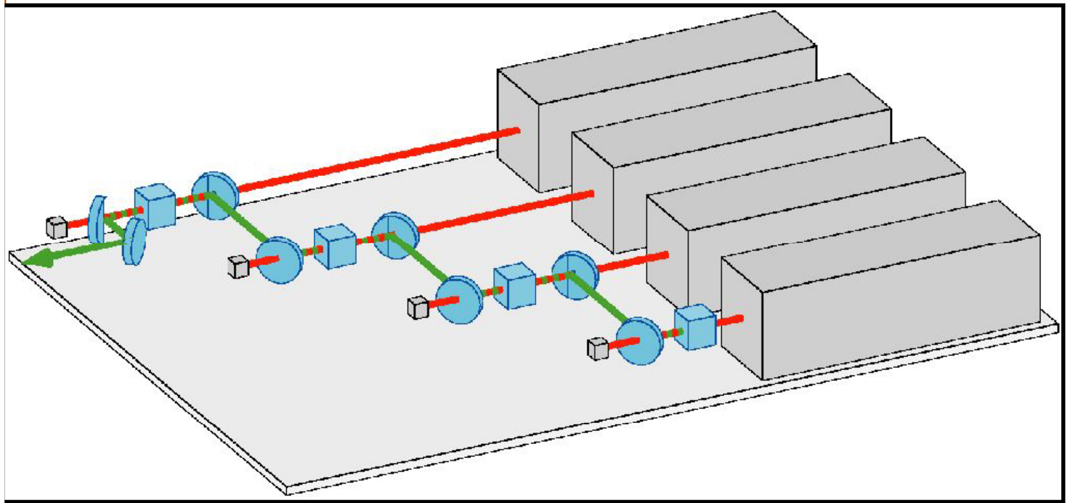
Dye laser

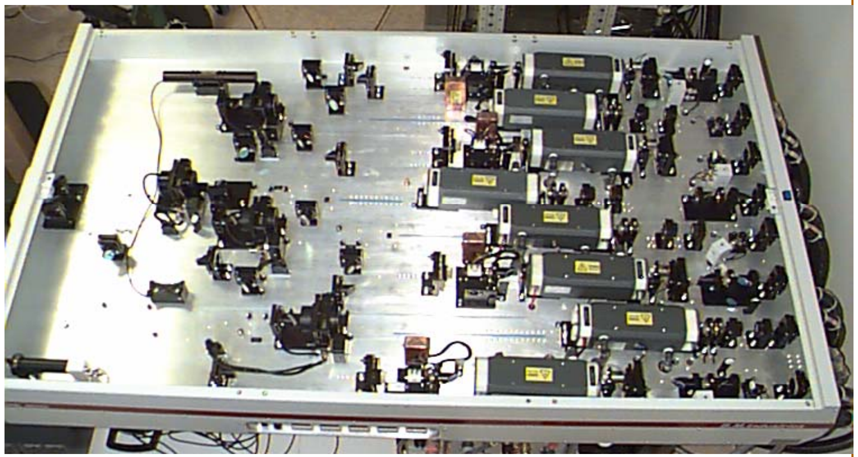
To cover all available wavelengths, different dyes are used



Different approaches for high speed visualization

- Multi YAG/framing camera approach





- 4 individual Nd:YAG lasers
- 4 pulses: time separation = 0-100ms
- 8 pulses: time separation = 7-145 ms
- Wavelengths: 532nm / 266nm

Specification- max rep rate: ~200 kHz (8 pulses),
max pulse energy ~400 mJ/pulse @ 532 nm
~ 80 mJ/pulse @ 266 nm

Possibility to pump dye lasers and OPO units for tunable radiation
Multiple dye lasers: 20–30 mJ/pulse @ 283nm
One OPO unit: ~10 mJ/pulse @ 283nm

(Thales)

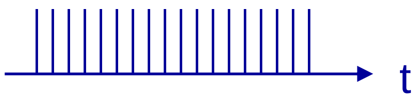
Different approaches for high speed visualization

- *Multi YAG/framing camera approach*

Specification- max rep rate: ~200 kHz (8 pulses)
max pulse energy ~400 mJ/pulse @ 532 nm (Thales)
~250 mJ/pulse @ 355 nm
~ 80 mJ/pulse @ 266 nm

Possibility to pump dye lasers and OPO units for tunable radiation
Multiple dye lasers: 20–30 mJ/pulse @ 283nm
One OPO unit: ~10 mJ/pulse @ 283nm

- kHz laser/CMOS high-speed camera approach

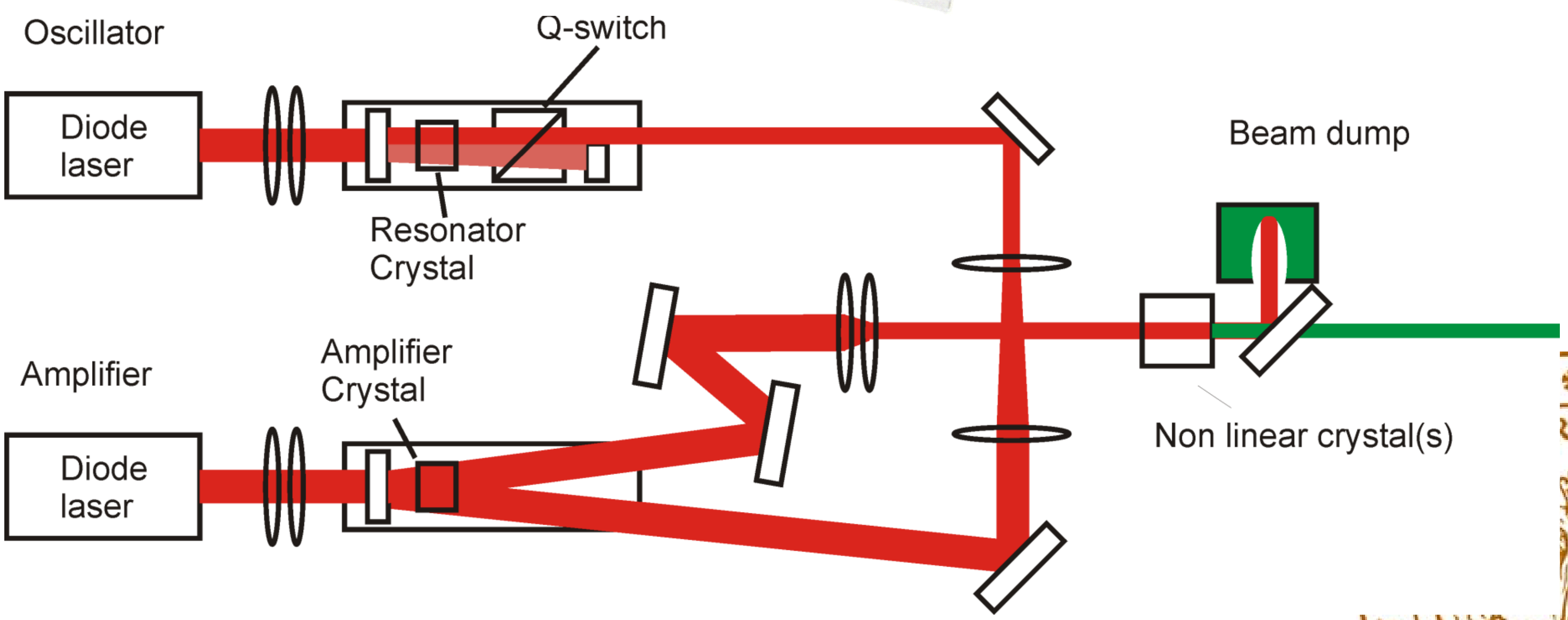


Applications: Transient phenomena, e.g;
Ignition
Extinction
Misfire
Flashback

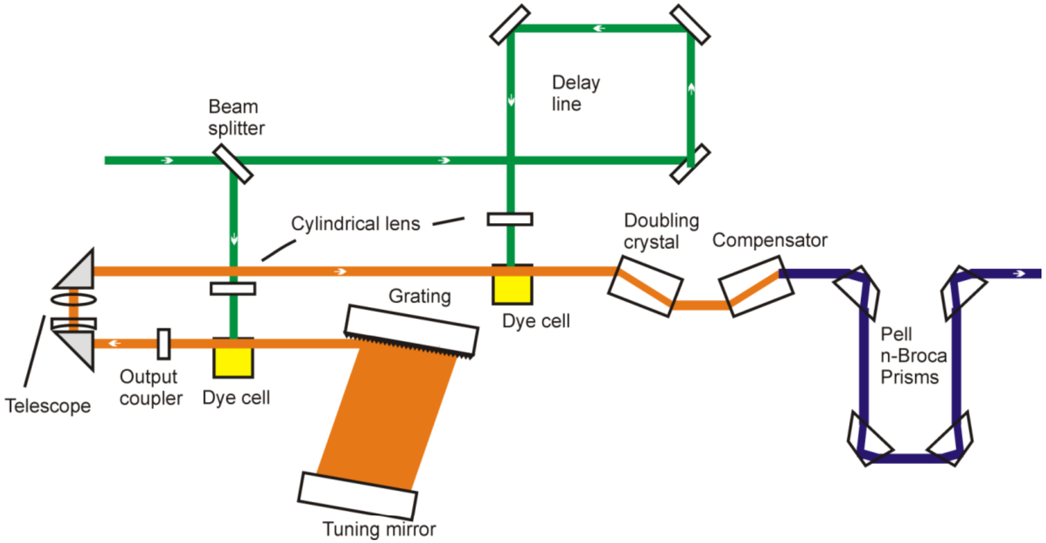
Specification- max rep rate: ~20 kHz
max pulse energy @ 10 kHz (Edgewave HD40IV-E):
~13 mJ/pulse @ 532 nm
~4 mJ/pulse @ 266 nm

Possibility to pump dye laser
~0.3 mJ/pulse @ 283 nm at 10 kHz

Characteristics - kHz Edgewave Nd:YAG



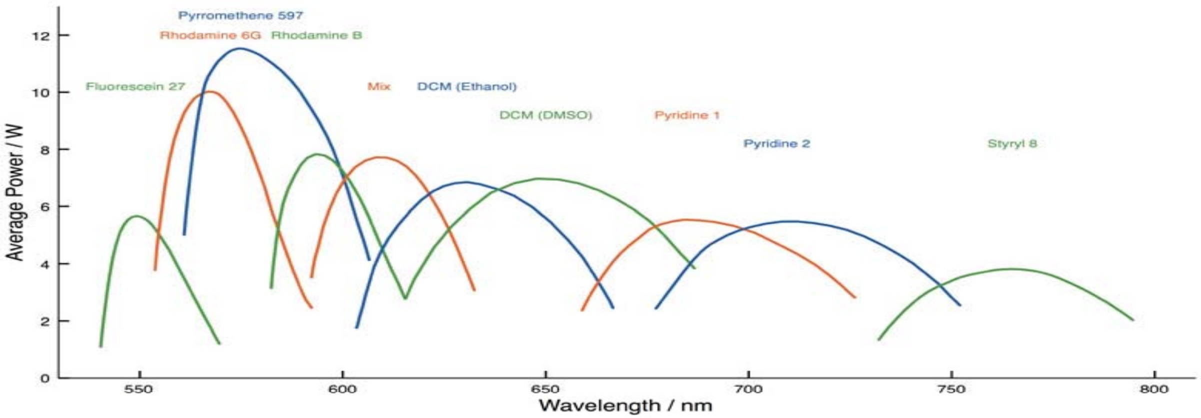
Characteristics - Sirah credo kHz dye laser



- Variable wavelength with frequency doubling

- Conversion efficiency of ~40 % at 566 nm (Rhodamine 6G)

- Maximum UV (OH) output 3W (300uJ @ 10kHz)



Wavelength extension techniques.
1. Frequency Doubling

- **Frequency doubling**

$$P = \chi_1 E + \chi_2 E^2 + \ldots\ldots$$

$$P = \chi_1 E_0 \exp(-i\omega t) + \chi_2 E_0^2 \exp(-i2\omega t) + \ldots\ldots.$$

- **Use doubly-refractive crystal to increase the efficiency by phase-matching**
- **Frequency mixing/tripling/sum/difference can also be achieved**

Characteristics

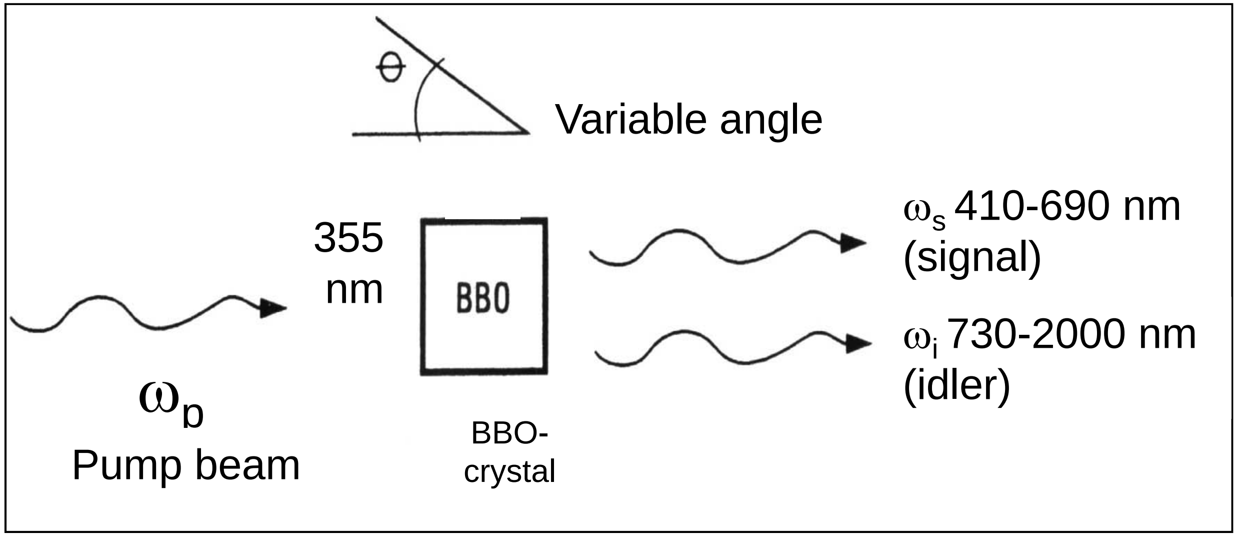
- Easy to apply
- High efficiency
- Scanning not possible if not continous tilting of the crystal
- Linewidth increase

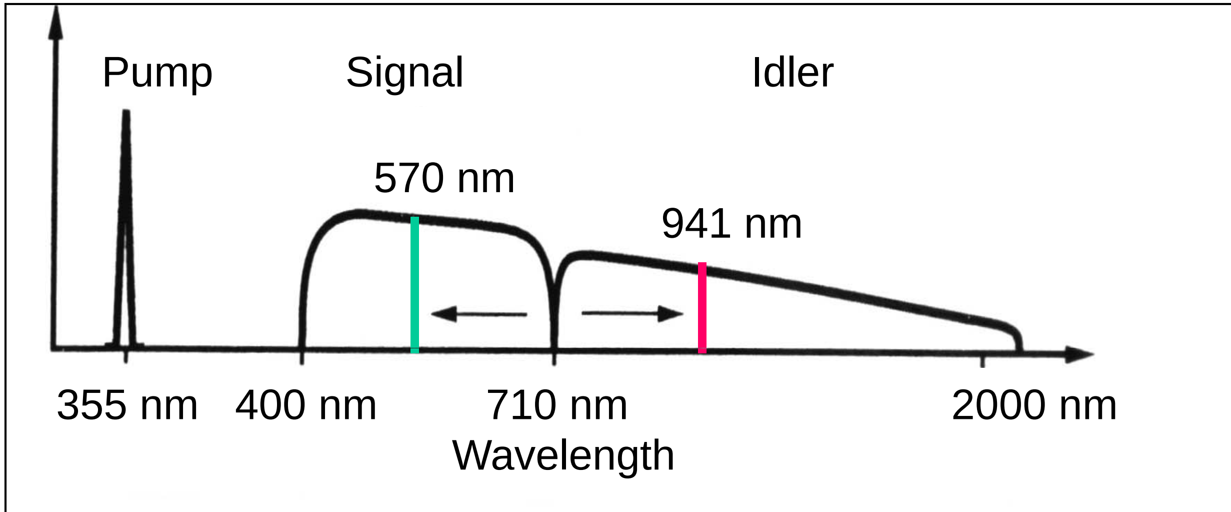
Wavelength extension techniques.
2 Optical parametric oscillator (OPO)

In an OPO, a pump beam is frequency converted to two other wavelengths in a crystal.

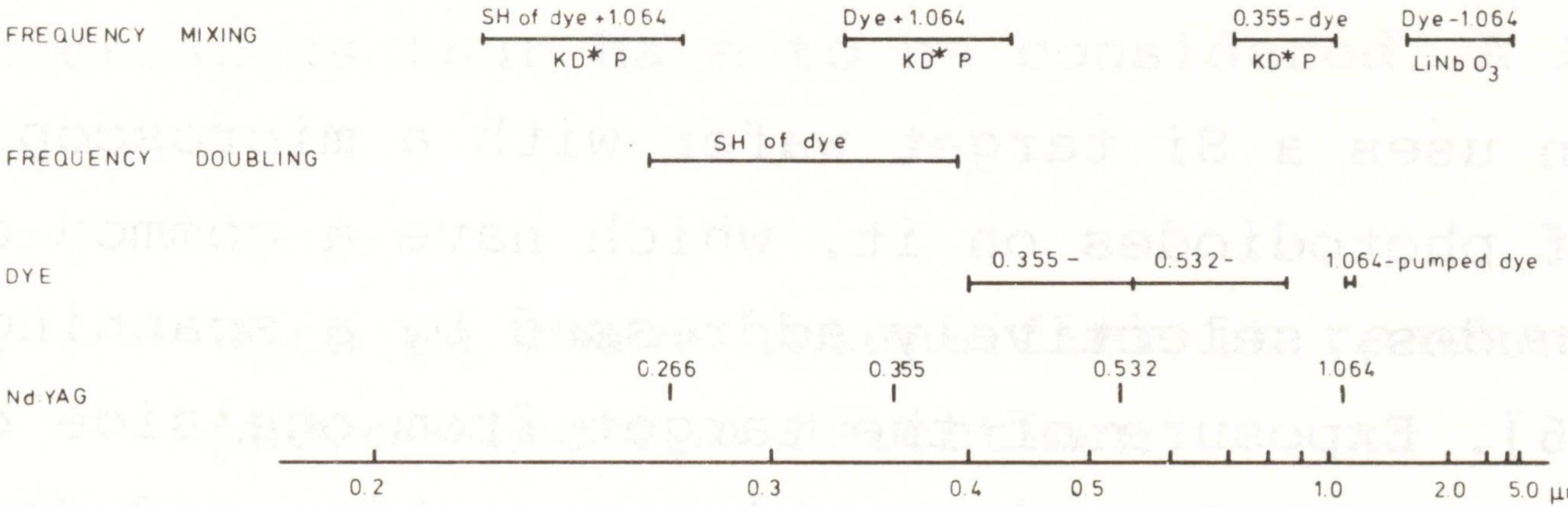
The output wavelengths depend on the angle of the crystal.

An OPO is easily tuneable in a large range of wavelengths.





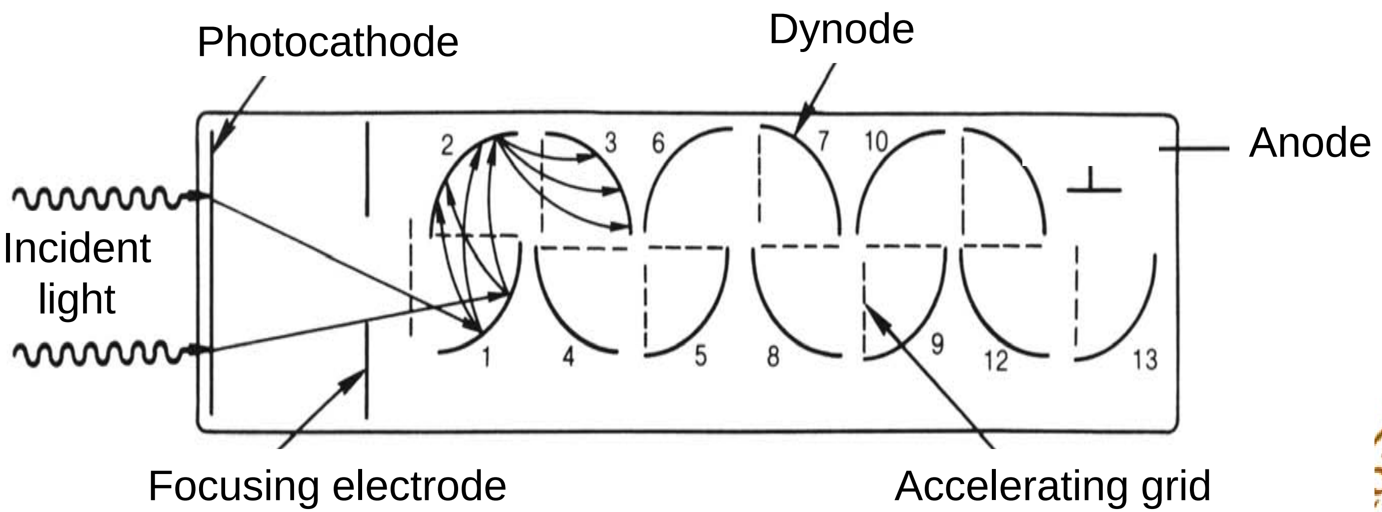
Wavelength extension techniques: Summary



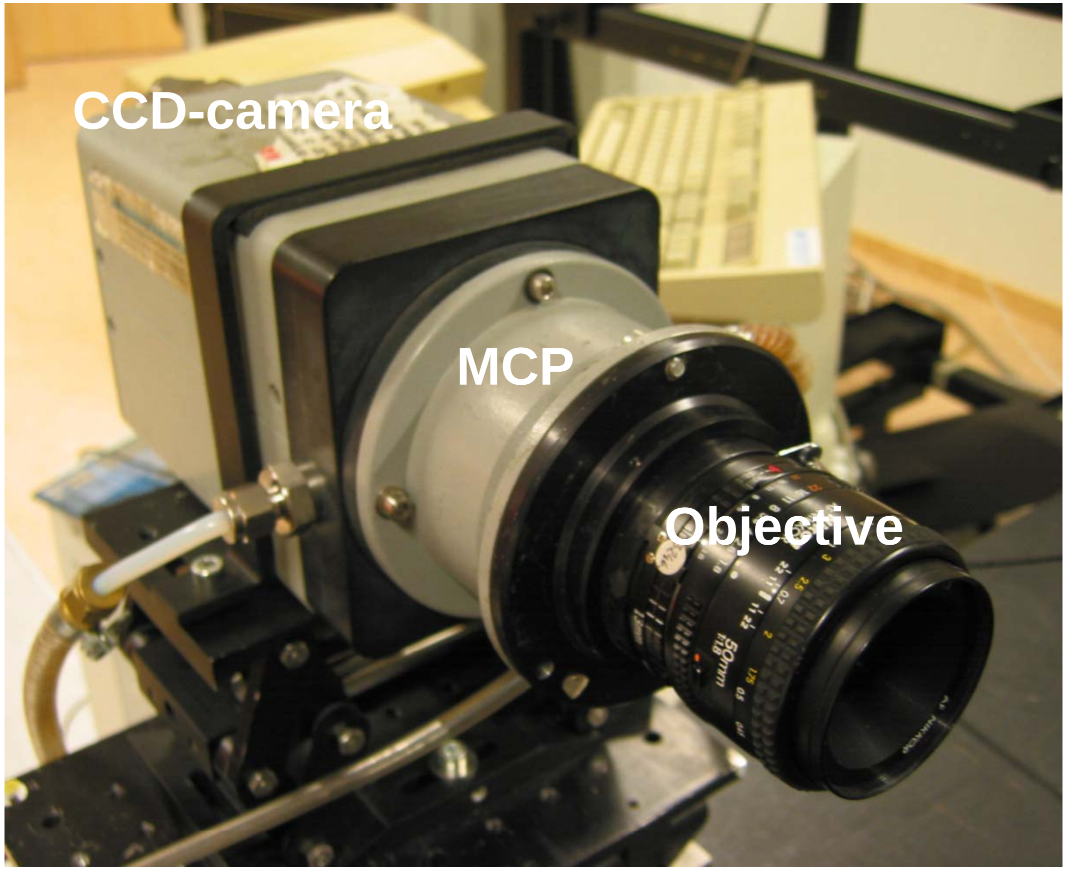
Detectors: Photomultiplier

A photomultiplier (PMT) is a sensitive detector, where incident radiation enters a cathode that strikes out electrons from a photocathode. They are then accelerated towards a series of dynodes giving rise to a large number of secondary electrons.

A photomultiplier is often used for time-resolved detection together with a digital oscilloscope.



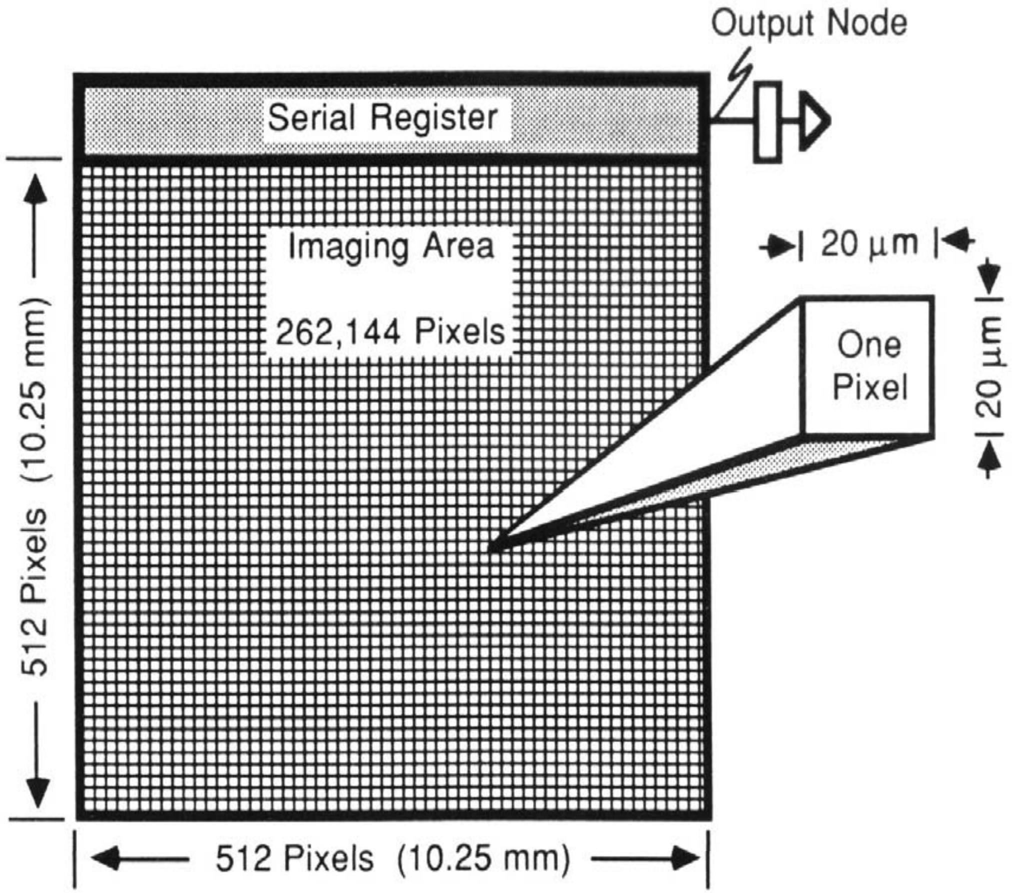
Detectors: Intensified charge couple device, ICCD



CCD- camera chip

The central unit in a CCD-camera is the CCD-chip.

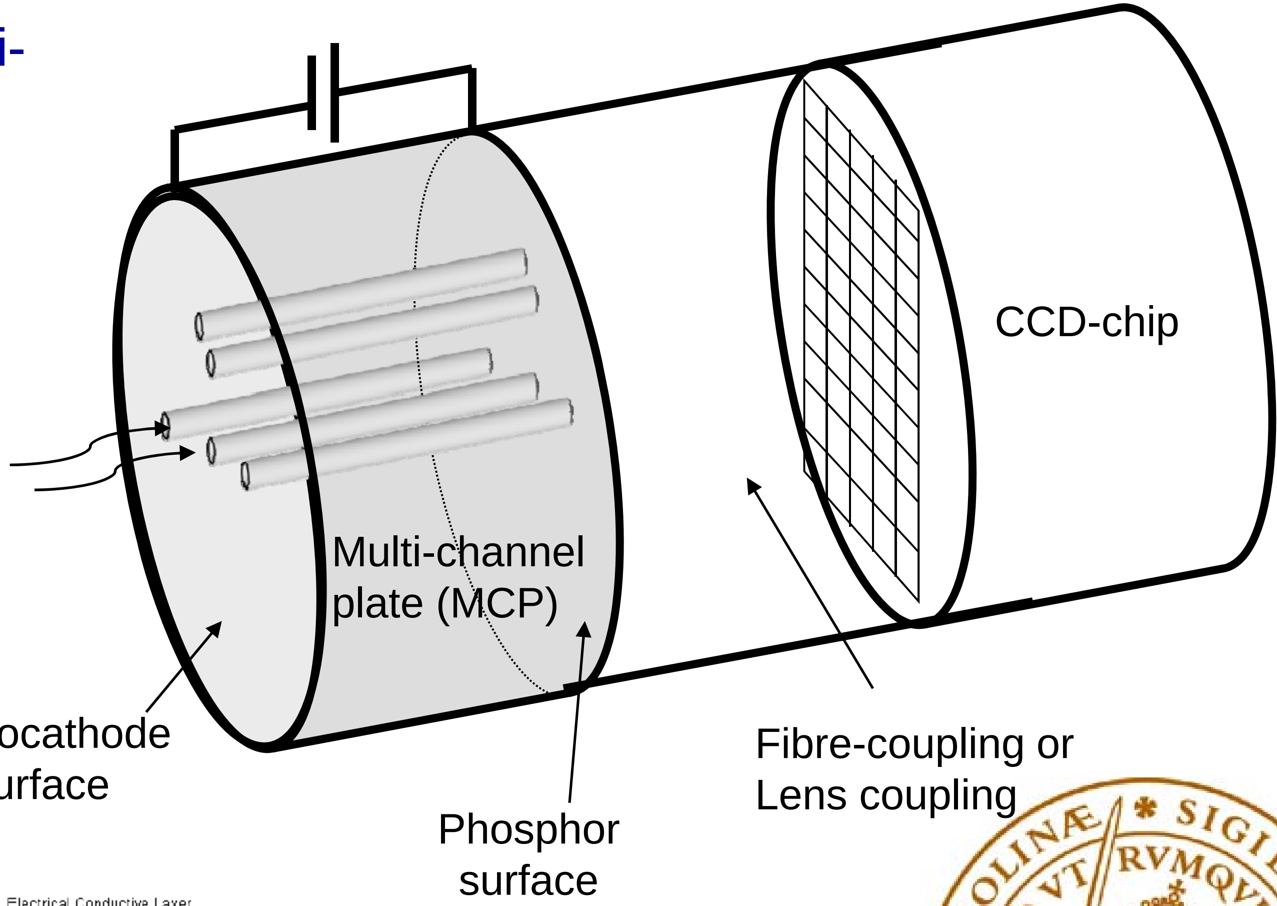
A pixel size of around 25 μm and a number of pixels of 512 x 512 is quite normal.

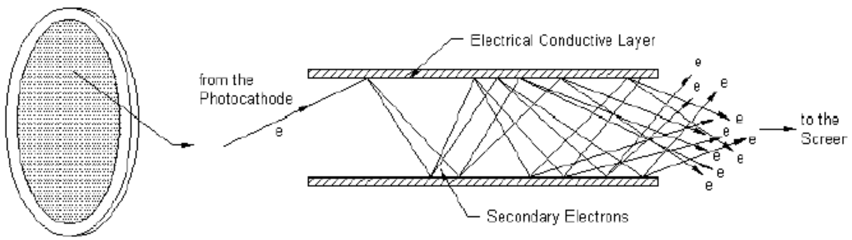


Detectors: Intensified charge couple device, ICCD

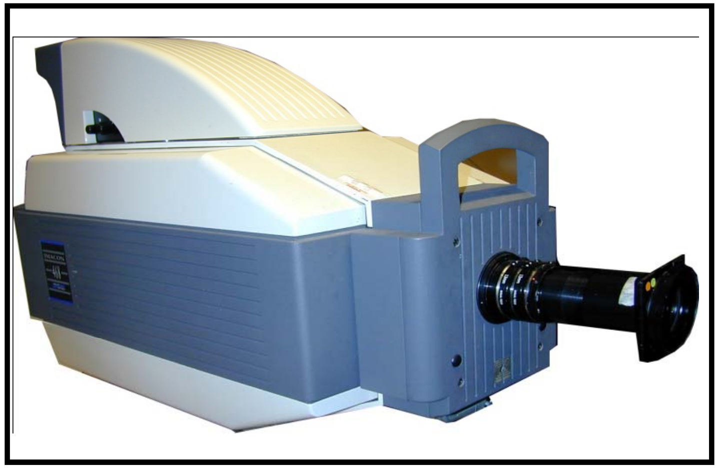
An image-intensified CCD-camera has a multi-channel plate in front of the CCD-chip.

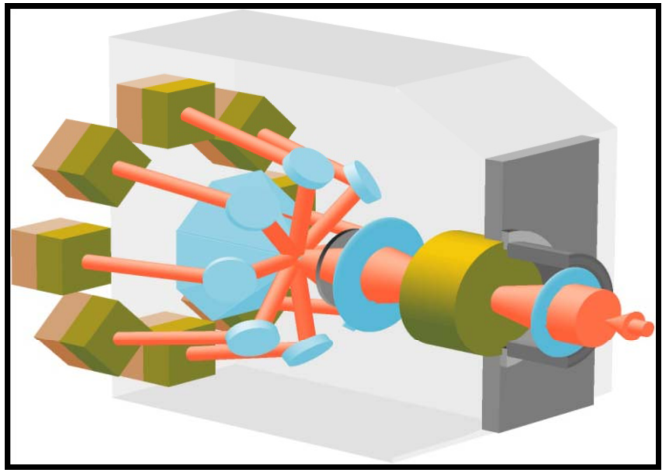
The purpose of this device is mainly to
- intensify the signal
- work as a time gate
- increase detected wavelength range





Framing camera

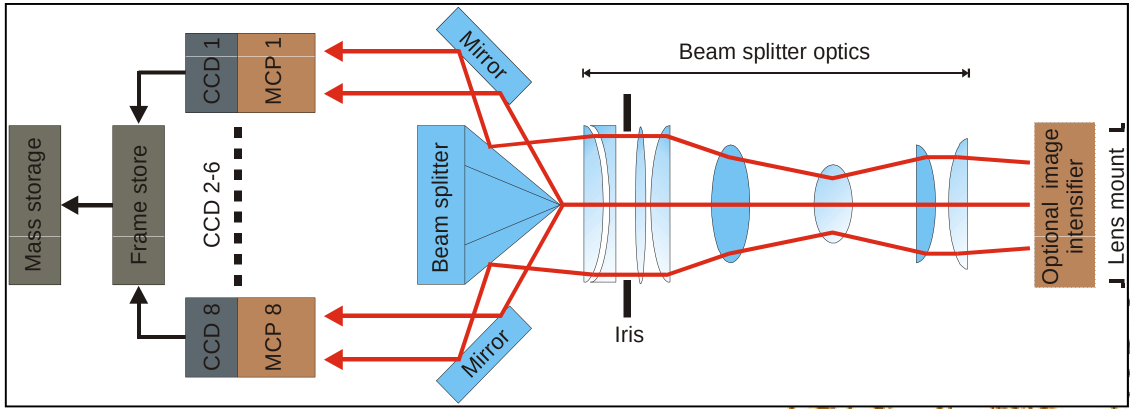




Custom modified high speed camera (Imacon 468, DRS Hadland, UK)

- 8 independent CCD's, 576x384 pixels 10 ns temporal resolution

- Optional image intensifier ⇒ UV sensitive - 1 μs temporal resolution



High speed camera

Photron
Fastcam SA5

Lambert image intensifier
HiCATT 25 Gen 2

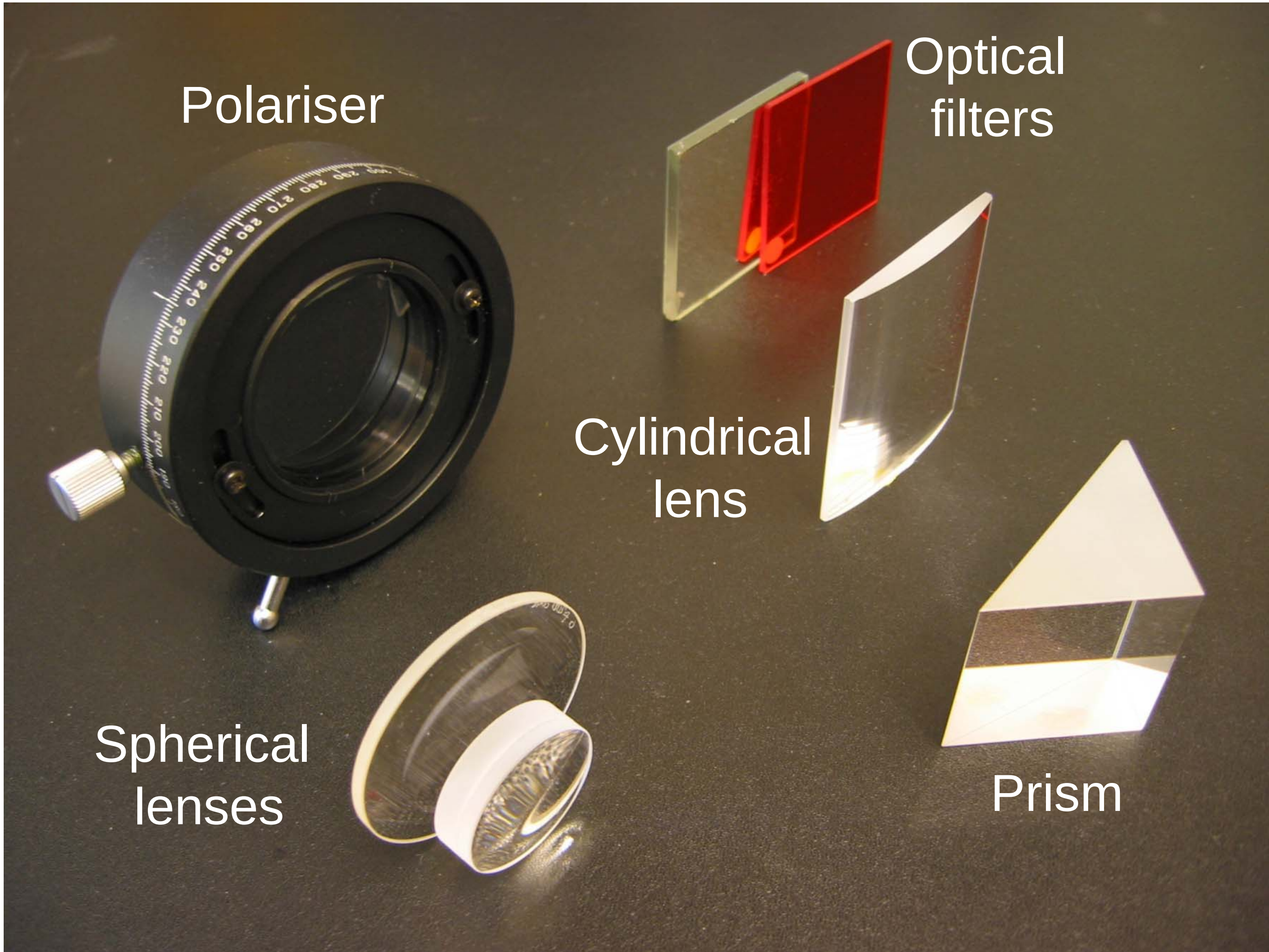
- 1024*1024 pixels at 7500 fps
- Up to 1 Mfps at reduced ROI

- Intensifies ~100 000 times
- Gate width down to 3ns

Some characteristics of CCD-cameras

Dynamic range	The number of charges that can be collected divided by the number of charges that is needed for detection above the noise level.
Quantum efficiency	The efficiency in conversion of photons to charges.
Wavelength sensitivity	The sensitivity of a CCD-chip to different wavelengths of incident radiation.
Read-out time	The time it takes between two recordings for a camera.
Binning	This means that the charge from several pixels, e.g 2x2, forms a “superpixel”. This increases sensitivity and decreases readout time.

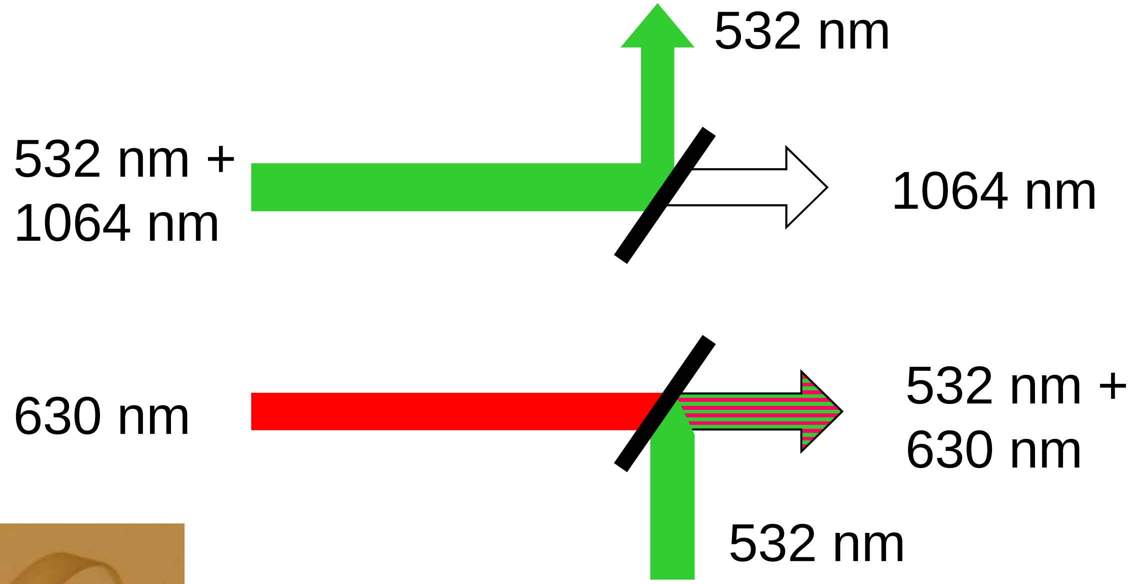
Optics



Polariser
Optical filters
Cylindrical lens
Spherical lenses
Prism

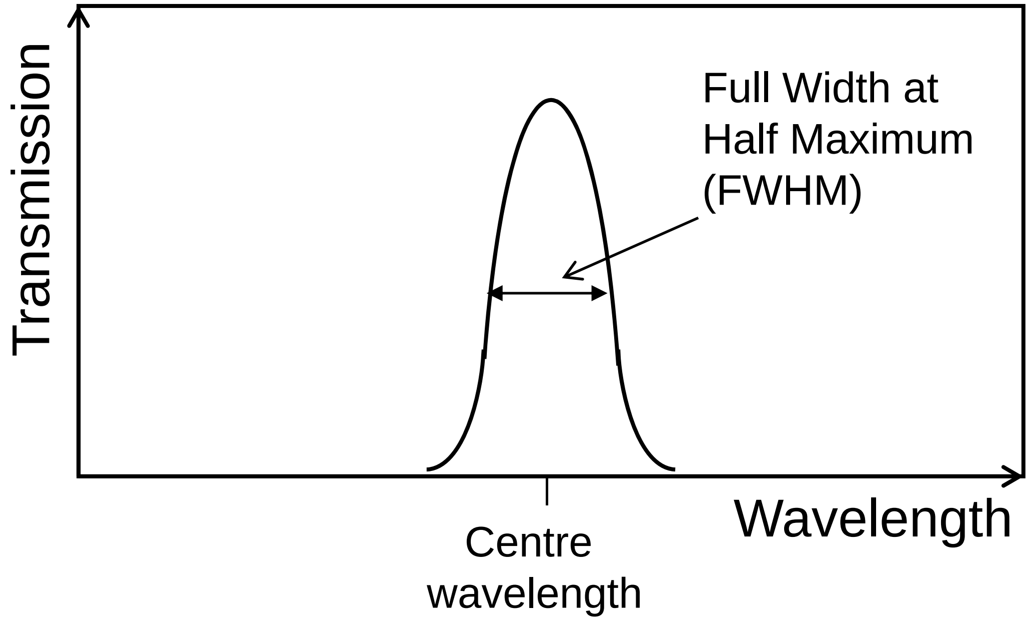
Overlapping / Separation of beams

- Dichroich mirrors are used to separate laser beams of different colours (wavelengths) from each other.
- They can be manufactured to reflect and transmit different wavelengths.



Interference filter

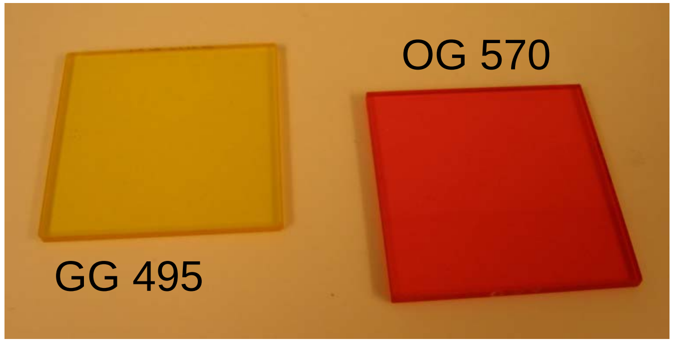
- An interference filter (IF) transmits a wavelength interval around a centre wavelength.
- The transmitted wavelength interval is given as FWHM and is normally 1, 3 or 10 nm.

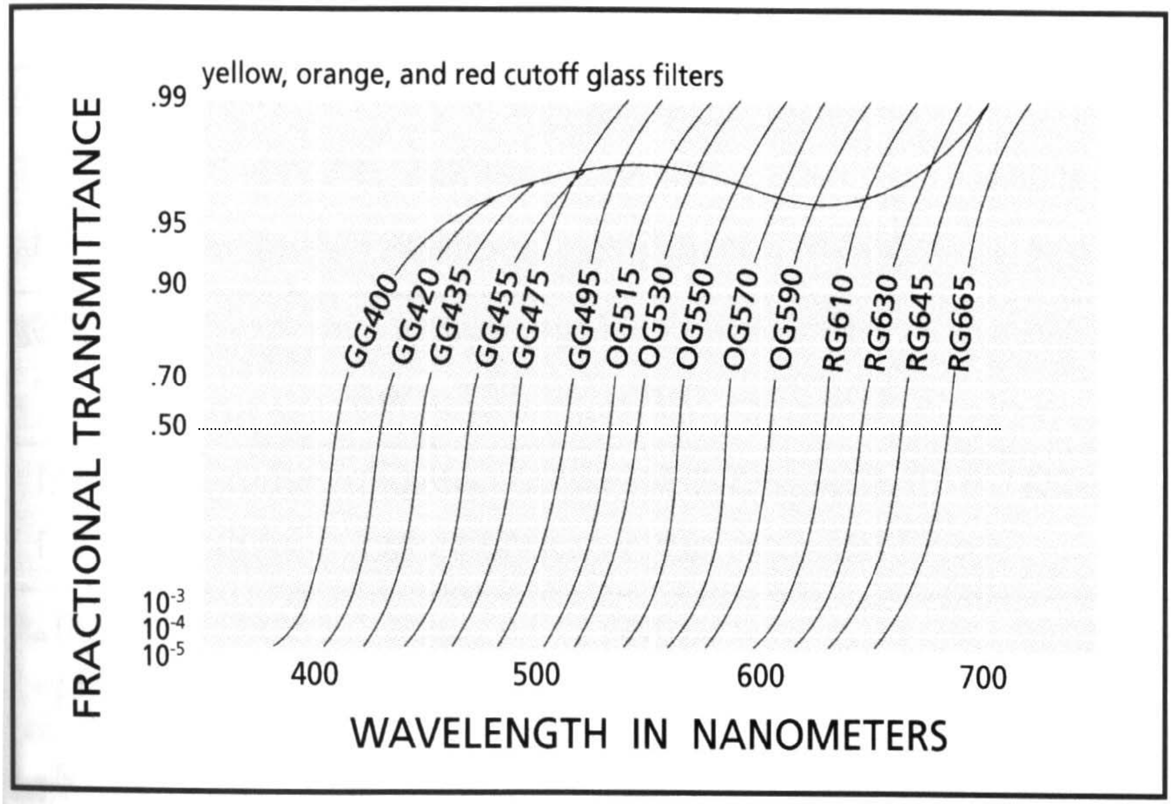


Interference filter with centre wavelength of 589.3 nm and with FWHM of 10 nm.

Long-pass filter

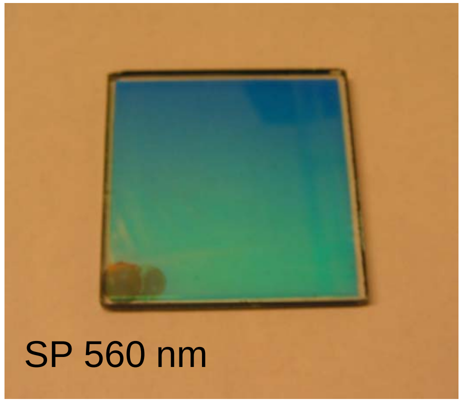
A long-pass filter transmits wavelengths longer than a specific wavelength. The wavelength for 50% transmission is often specified.

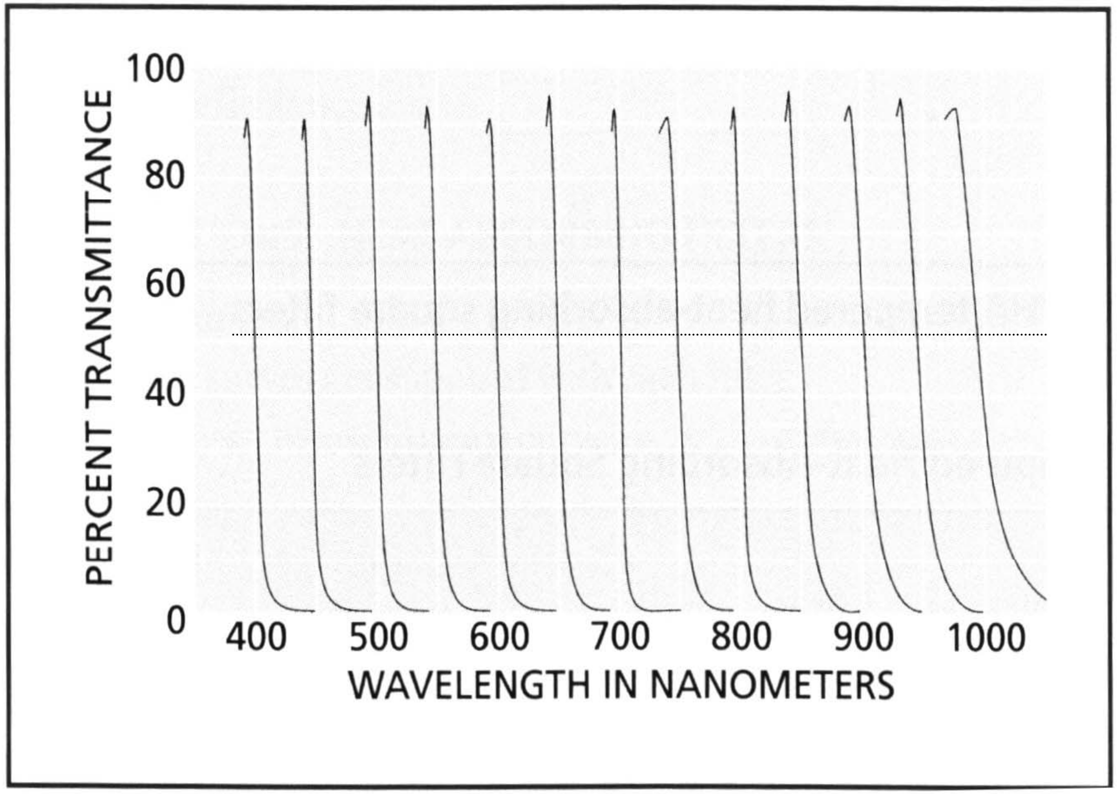




Short-pass filter

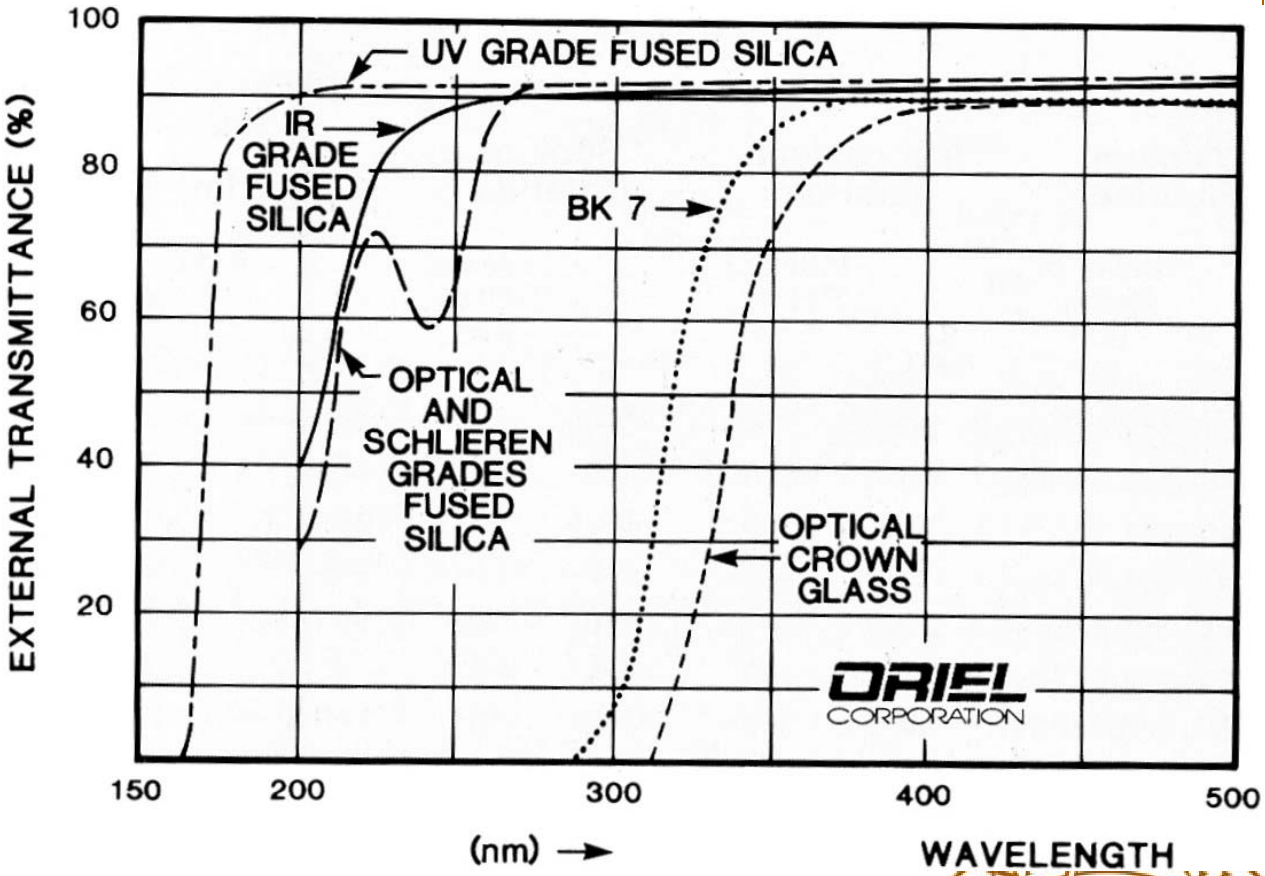
A short-pass filter transmits wavelengths shorter than a specific wavelength. The wavelength for 50% transmission is often specified.





Window material

- Spectroscopy is often applied at wavelengths in the ultraviolet region (<400 nm).
- When working with wavelengths in the range 200 - 350 nm, normal glass can not be used because of a low transmission.
- Glass of fused silica or sapphire must then be used instead.

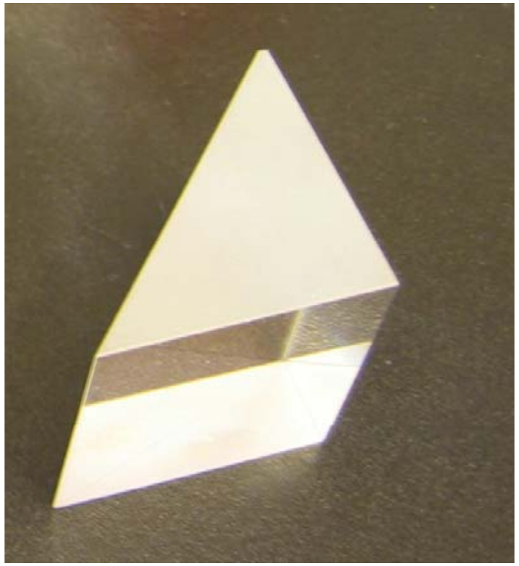


Prisms

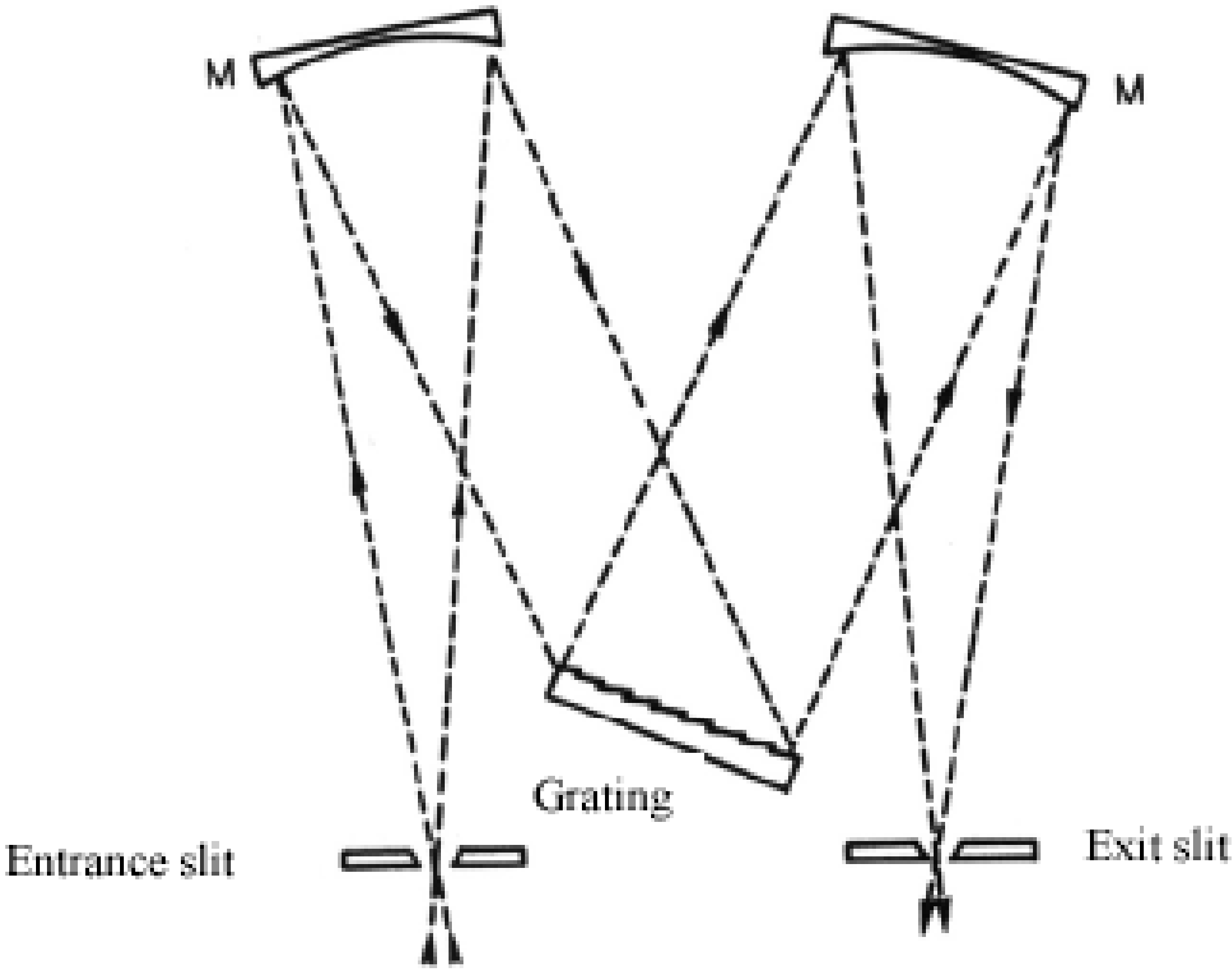
There are different kinds of prisms that can be used for different tasks.

Examples:

- to separate different polarisations of the light
- to separate beams of different wavelengths
- to improve the polarisation of a beam
- to reflect a beam 90 degrees
- to reflect a beam 180 degrees (as a delay line)



Spectrograph/monochromator



Imaging spectrograph