Optics, Laser and Detection

in Modern Experimental Techniques

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Outline

- ABC of optical components

  - Optics, opto-mechanics, vibration isolation and motion control

- Know your laser system

  - Basic principles, laser engineering, frequency conversion and laser safety

- Detect optical radiation

  - Intensity, wavelength, polarization and phase

- Build an optical instrument

  - Initial concept, computer drawing/simulation, revision and construction

- Examples

  - Interferometer and laser processing machine

References

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- **Books:**

Fundamentals of Photonics, B. E. A. Saleh and M. C. Teich (John Wiley & Sons, New York, 1991)

Laser Spectroscopy: Basic concepts and instrumentation, W. Demtröder (Springer-Verlag, Berlin, 1996)

Building Scientific Apparatus, J. H. Moore, C. C. Davis, M. A. Coplan (Perseus Books, Cambridge, 2003)

- **Company websites:**

www.newport.com; www.mellesgriot.com; www.cvilaser.com; www.coherentinc.com

- **Directories:**

www.laserfocusworld.com

www.photonics.com

Teaching practices

- Building up conceptual connection between theory and experiment
- Knowing experimental apparatus and tools
- “Think before act”
- Hand-on experience on optical alignment

Actual design vs. schematic layout

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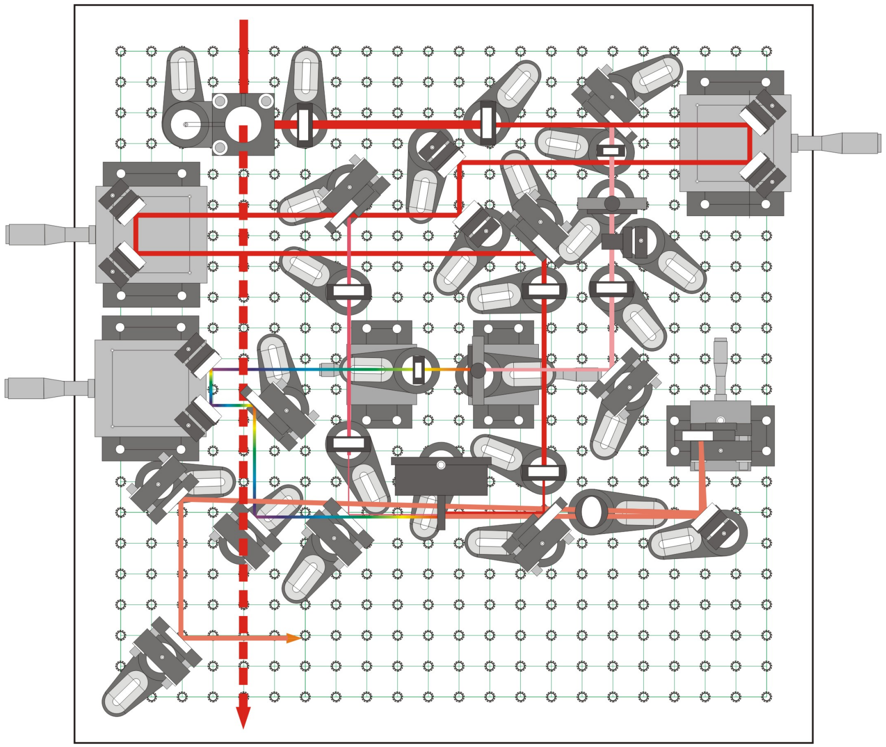
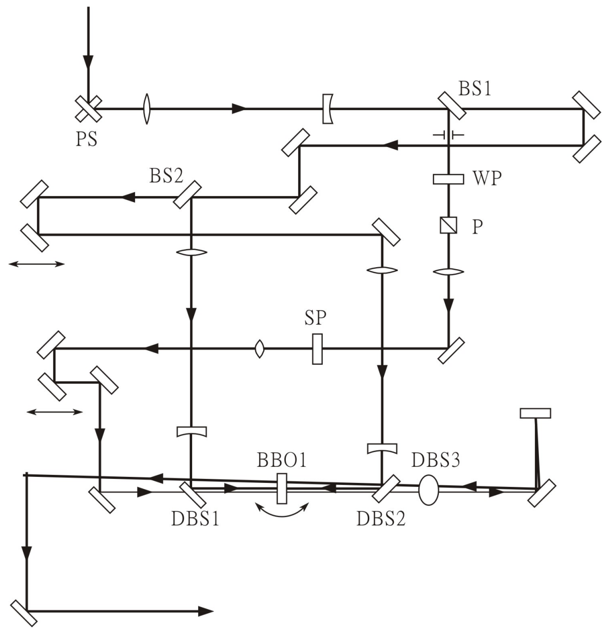
Actual design



Schematic layout



Course requirement

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- A construction plan for an optical setup (40%)

  - It should contain a computer drawing, a purchasing list of parts, and a report.

  - The design should be composed of light source(s), optical and opto-mechanic components, and detector(s).

  - Both top and side views of the drawing should be provided. It should be laid out on a breadboard or an optical table. An example of computer drawing is given in the lecture.

  - The list of parts should contain specification which describe the important information why they are chosen.

  - The total number of items (optic and opto-mechanic components) should be more than ten. Jointed effort by several people is encouraged. However, the number of components will be added up.

  - The grade will depend on its innovativeness, completeness, and functionality.

  - A one-page proposal (5%) needs to be submitted to teaching assistants (TAs) before September 23.

  - A final report (35%) needs to be submitted to TAs before November 11.

- A hand-on experiment of Twyman-Green interferometer (40%)

  - A note will be released by TAs before September 4. The lab time will be arranged with TAs.

  - Each student will be asked to measure the refractive index of an unknown right-angle prism.

  - On October 7, in-lab evaluation (20%) on the optical alignment procedure will be performed. Each student has 15 minutes to complete the alignment.

  - A final report (20%) needs to be submitted to TAs before November 11.

- Class attendance (20%)

  - The attendance rates in lectures and assigned experiments are accounted for in the grading.

  - No grade for no attendance in all the lectures.

Intensity and photon nomogram

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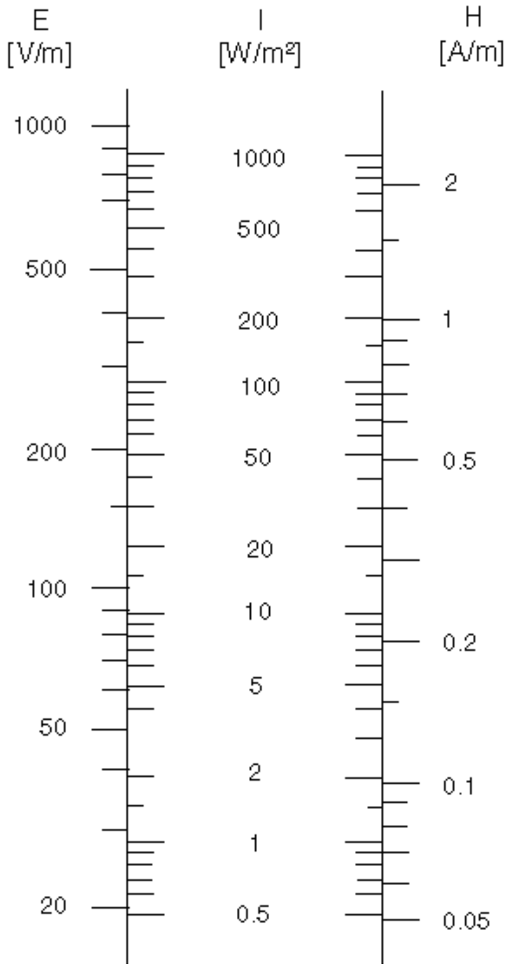
$$E = \eta H, \quad H = \frac{E}{\eta}, \quad \eta = \frac{E}{H}$$

$$I = \frac{EH}{2}, \quad I = \frac{E^2}{2\eta}, \quad I = \frac{\eta H^2}{2}$$

$$E = \sqrt{2\eta I}, \quad H = \sqrt{\frac{2I}{\eta}}$$

$$\eta_0 = 377 \text{ ohms } (\Omega)$$

$$\eta = \frac{\eta_0}{n}$$

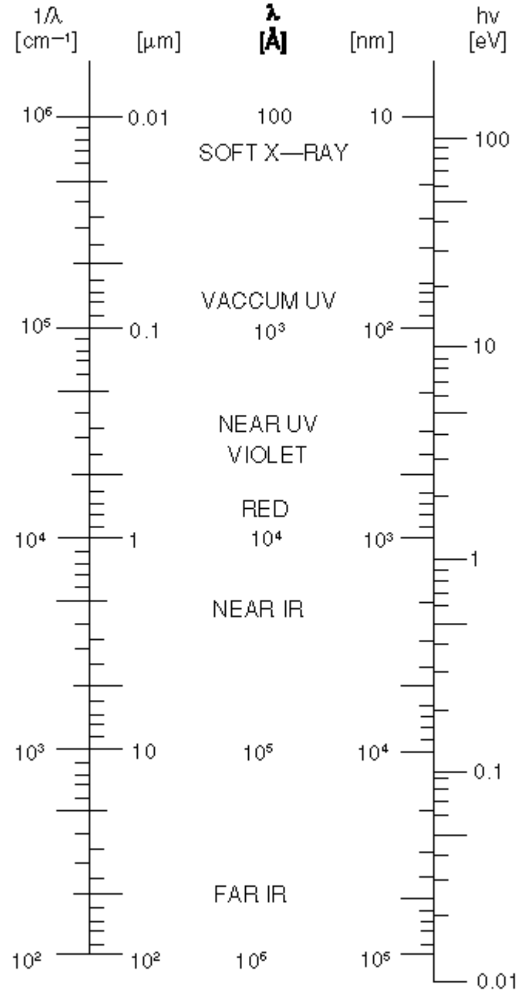


Wave Number $(\nu)[cm^{-1}]$

$$= \frac{10^7}{\lambda_0}[nm]$$

Electron volts (eV) per photon

$$= \frac{1242}{\lambda_0}[nm]$$



Basics of Gaussian beam optics

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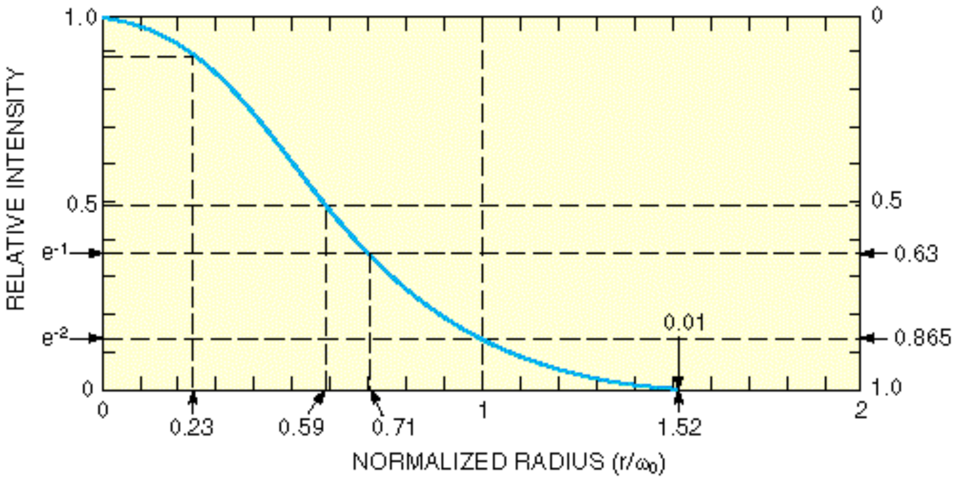
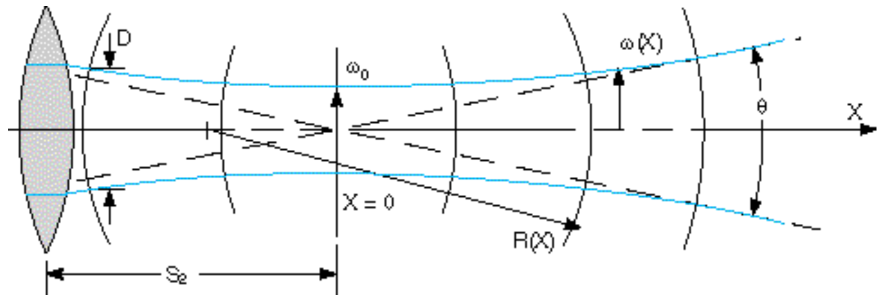
- **Gaussian intensity distribution**

$$I(r) = I(0)\exp\left(-\frac{2r^2}{\omega_0^2}\right)$$



- **Gaussian beam focusing**



Beam waist

$$2\omega_0 = \left(\frac{4\lambda}{\pi}\right)\times(f/\#) = \left(\frac{4\lambda}{\pi}\right)\times\left(\frac{F}{D}\right)$$

Depth of focus

$$DOF = \left(\frac{8\lambda}{\pi}\right)\times(f/\#)^2 = \left(\frac{8\lambda}{\pi}\right)\times\left(\frac{F}{D}\right)^2$$

Optics Glossary

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- **Aberration**: An optical defect resulting from design or fabrication error that prevents the lens from achieving precise focus. The primary abberrations are spherical, coma, astigmatism, field curvature, distortion and chromatic aberration.
- **Damage Threshold**: The maximum energy density to which an optical surface may be subjected without failure.
- **Diffraction Limited**: Describes an optical system in which the quality of the image is determined only by the effects of diffraction and not by lens aberrations.
- **F-Number**: A measure of the ability of a lens to gather light, represented by f/# . The ratio of the focal length of the lens to its effective aperture. Related to numerical aperture by $f/\# \approx 1/(2NA)$.
- **Numerical Aperture**: Given by sine of the half-angle of the maximum cone accepted by an optical system.
- **Scratch-Dig**: A measure of the visibility of surface defects as defined by U.S. military standard MIL-PRF-13830B. The ratings consist of two numbers, the first denoting the visibility of scratches, the second, of digs (small pits). Scratch numbers are linear with a #10 scratch appearing identical to a 1.0 μm wide standard scratch on glass. Similarly, a #1 dig appears identical to a 0.01 mm diameter standard pit.
- **Surface Figure**: A measure (in terms of wavelengths of light) of how closely the surface of an optical element matches a reference surface.

Aberrations

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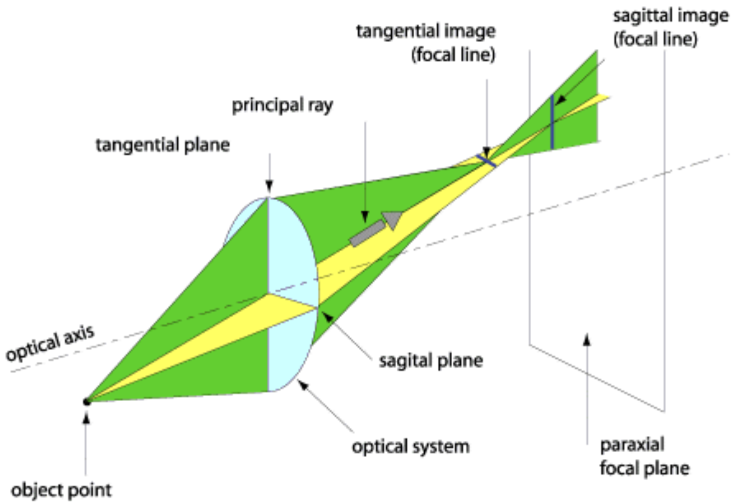

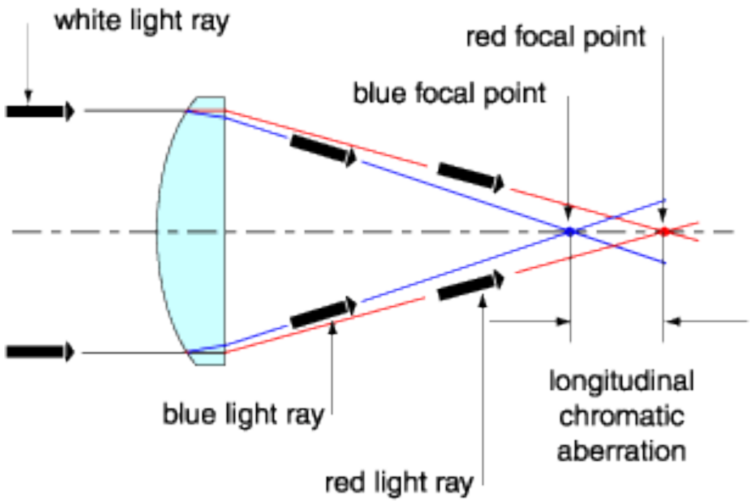

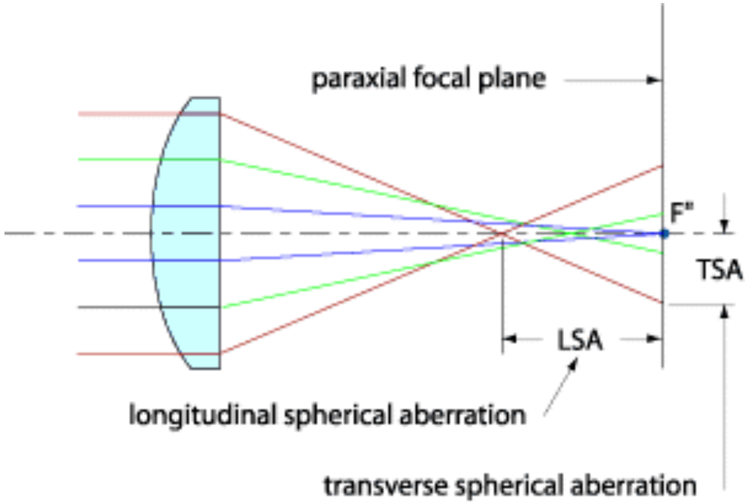

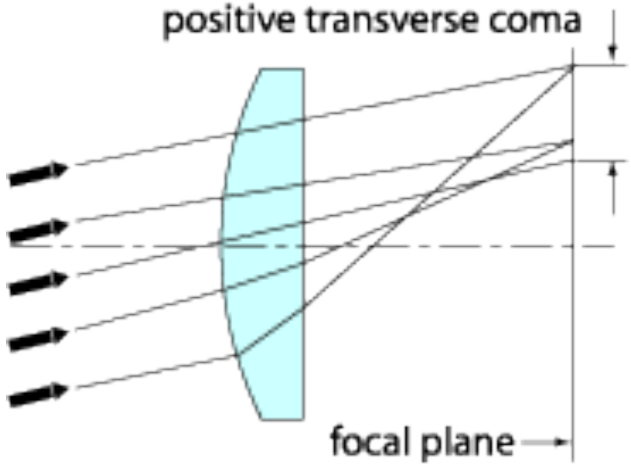

Aberration of different lens shapes

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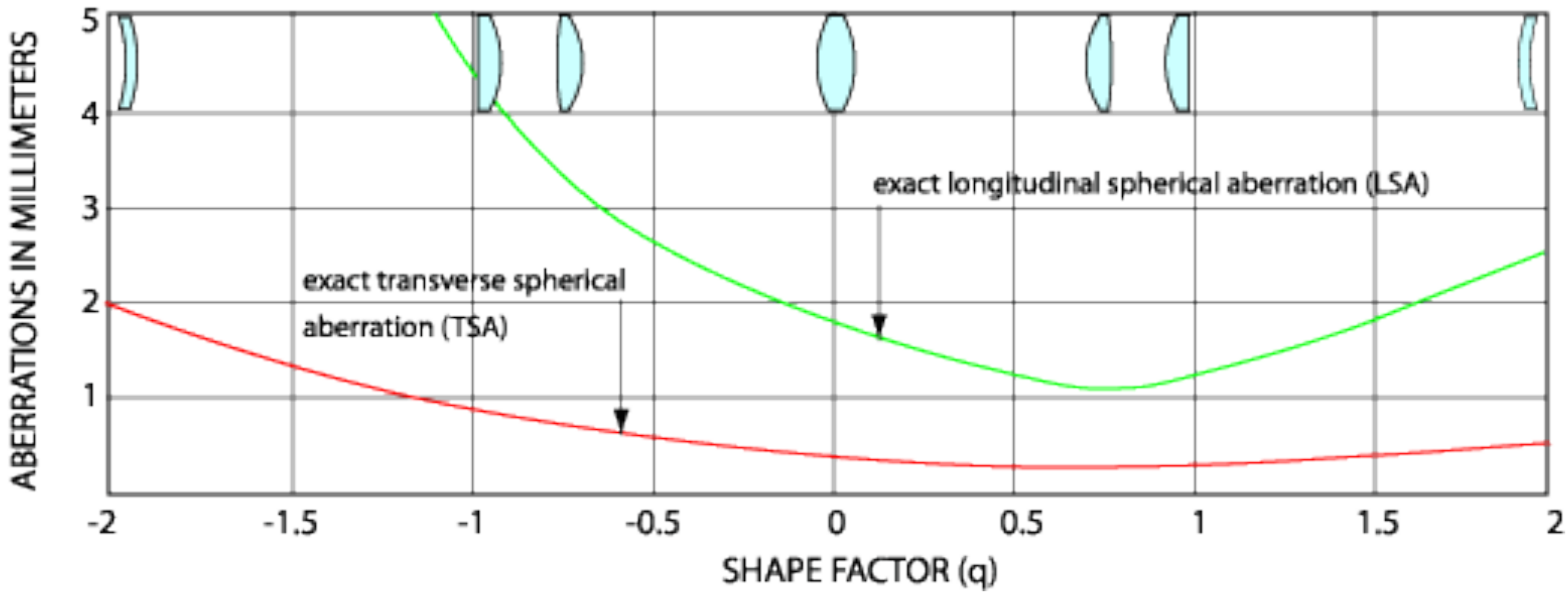
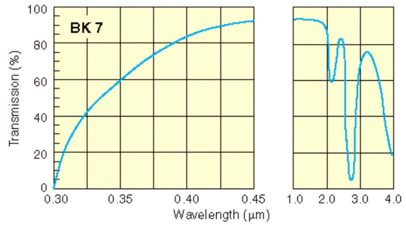
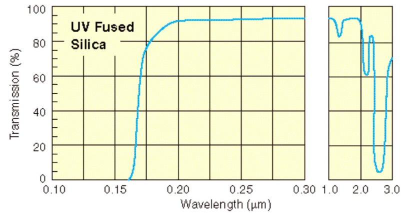


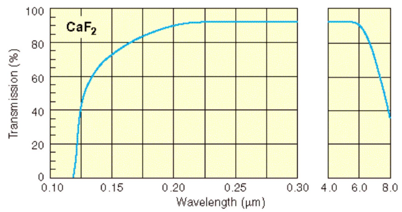
- The ideal shape is determined by the situation and may require rigorous ray-tracing analysis.
- It is possible to achieve much better correction in an optical system by using more than one element.

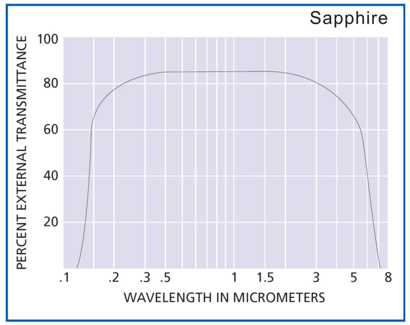
Optical materials

- **BK 7** is one of the most common borosilicate crown glasses used for visible and near infrared optics. The transmission range for BK 7 is 380-2100 nm.
- **UV grade fused silica** is synthetic amorphous silicon dioxide of extremely high purity. This non-crystalline, colorless silica glass combines a very low thermal expansion coefficient with good optical qualities, and excellent transmittance in the ultraviolet.
- **Calcium Fluoride (CaF_2)** is a cubic single crystal material with good vacuum UV to infrared transmission. It is sensitive to thermal shock, so care must be taken during handling.
- **Sapphire** is a synthetic hexagonal crystal form of aluminum oxide with good transmission from 250-5500 nm. Sapphire exhibits high mechanical strength, chemical resistance, and thermal stability. However, its birefringence property limits its optical usage.









Metallic mirrors-I

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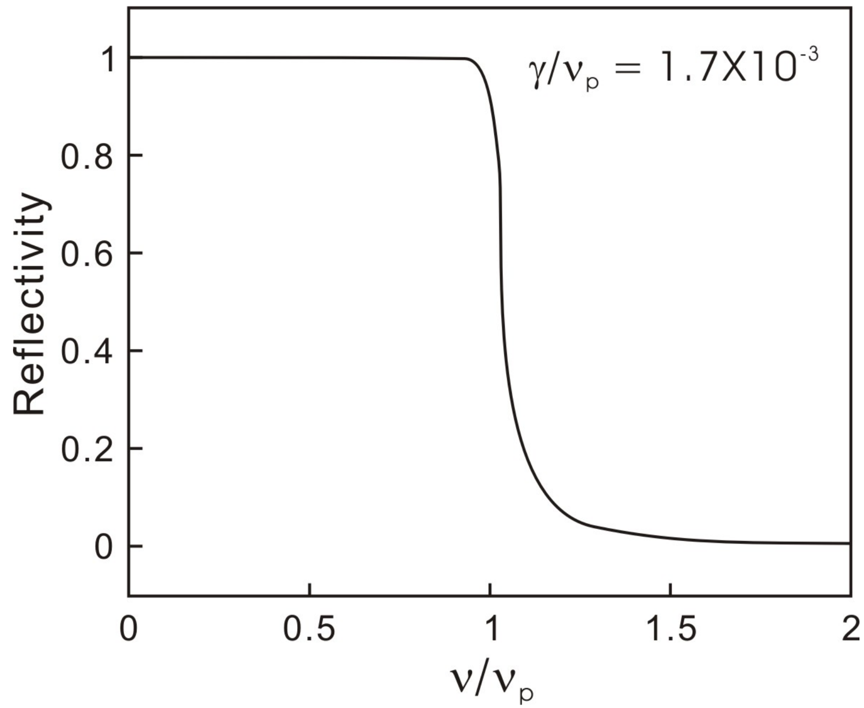
- Wide reflectance spectral range
  - Drude model
- Low dispersion
  - good for ultrafast laser pulses
- Medium reflectivity
  - 85-95%
- Less sensitivity to incident angle
- Low laser damage threshold
  - 100 W/cm^2 (CW)
  - 0.3 J/cm^2 (10 ns)



$$\varepsilon(\nu) = 1 - \frac{\nu_p^2}{\nu^2 + i4\pi^2 c\nu\gamma}, \quad \nu_p^2 = \frac{Ne^2}{\pi m}$$

Metallic mirrors-II

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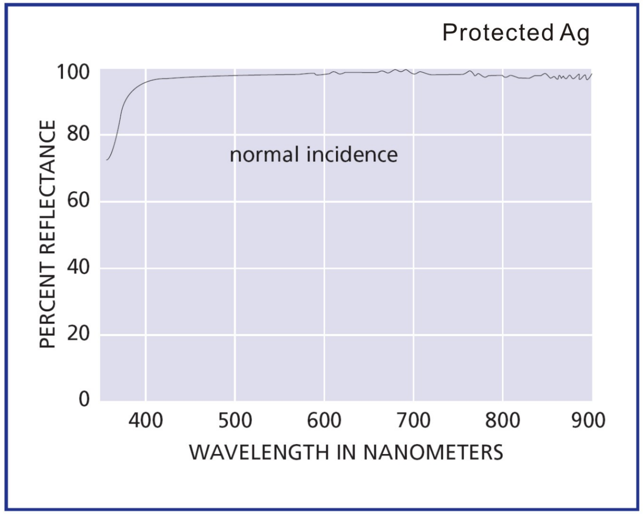

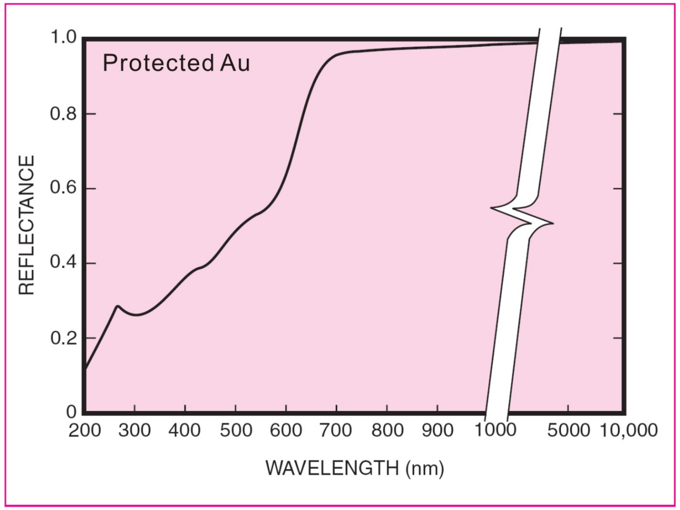

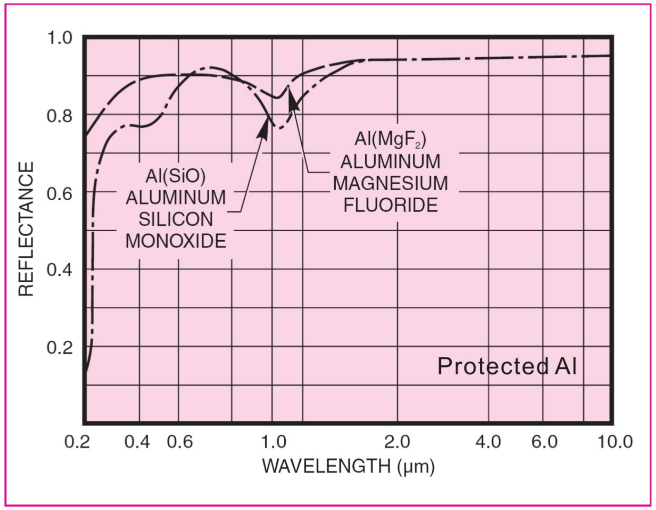

- **Ag-coated mirrors:** Ag is easily oxidized in air. Protected coating endure its lifetime. Its reflectance limits to >400 nm.
- **Au-coated mirrors:** Au is soft and requires protected coating. For bare Au coating (such as in gratings), no cleaning is allowed. Its reflectance limits to >700 nm.
- **Al-coated mirrors:** Al is easily oxidized in air and requires protected coating. Its reflectance limits to >250 nm. There is a dip in reflectance from 800 to 1000 nm.

Anti-reflection optical coating

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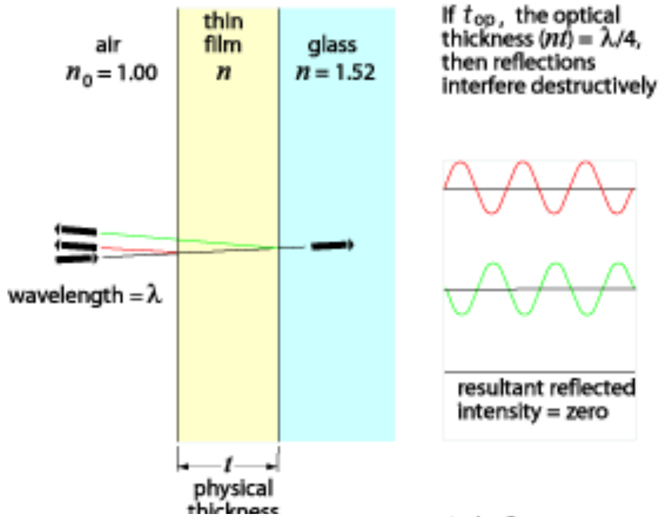
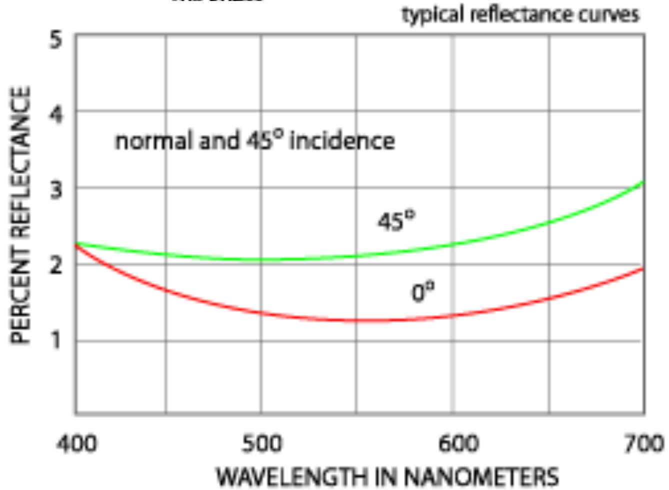
- **Anti-reflection coatings** can reduce overall transmission loss, minimize stray light, and prevent back reflections. Stray light in the wrong place can swamp the desired signal, making a measurement impossible. Reflected laser beams can burn absorbing surfaces, form unwanted foci, and pose safety hazards, while back-reflected beams can destabilize laser oscillators.
- The thickness of a single-layer antireflection film must be an odd number of quarter wavelengths in order to achieve the correct phase for cancellation. There is a $\pi/2$ phase shift for reflections at both interfaces. These identical phase shifts cancel each other out. The net phase shift between the two reflections is determined solely by the optical path difference $2t$ x n_c, where t is the thickness of the coating layer and n_c is the refractive index of the coating. The phase shift is $2tn_c/\lambda$.





High-reflection optical coating

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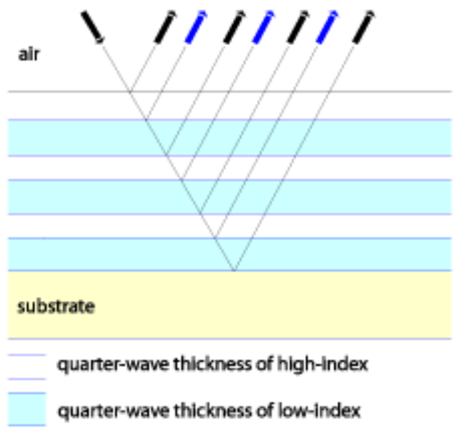
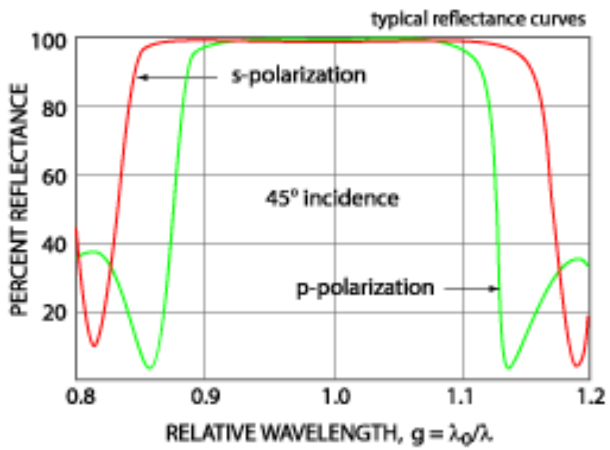
- In **high-reflectance dielectric coatings**, quarter-wave thicknesses of alternately high- and low-refractive index materials are applied to the substrate. The various reflected wavefronts can be made to interfere constructively to produce a highly efficient reflector.
- The peak reflectance value is dependent upon the ratio of refractive indices of the two materials, as well as the number of layer pairs. Increasing either increases the reflectance. The width of the reflectance curve (versus wavelength) is also determined by the film refractive index ratio. The larger the ratio, the wider the high-reflectance region.
- Reflectance of such films can easily be made to exceed the highest metallic reflectances over limited wavelength intervals.
- Because of the materials chosen for the multilayer, durability and abrasion resistance of such films are normally superior to those of metallic films.





Quality parameters of optical coating

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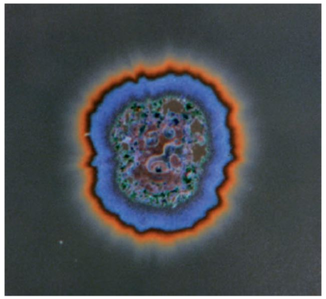
Specification	Parameter	Unit	Standard	Measurement principle
Laser-induced damage threshold (LIDT)	cw-LIDT	W/cm	ISO 11254-1	Cw-laser irradiation
	1 on 1-LIDT	J/cm^2	ISO 11254-1	Irradiation with single pulses
	S on 1-LIDT	J/cm^2	ISO 11254-2	Repetitive irradiation with pulses
	Certification	J/cm^2	ISO 11254-3	Irradiation sequence
Optical losses	Absorptance	ppm	ISO 11551	Laser calorimetry
	Total scattering	ppm	ISO 13696	Integration of scattered radiation
Transfer function	Reflectance	%	ISO 13697	Precise laser ratiometric method
	Transmittance	%	ISO 15368	Spectrophotometry
Surface quality	Form tolerances Scratch/digs Roughness	λN	ISO 10110	13 parts containing different types of imperfections
Stability	Abrasion		ISO 9211	Different test methods
	Environmental Stability		ISO 9022	21 parts containing a variety of conditioning methods



A typical example of laser-induced damage on optical coating

Springer Handbook of Laser and Optics, ed. F. Träger (Springer, New York, 2007).

Polarization

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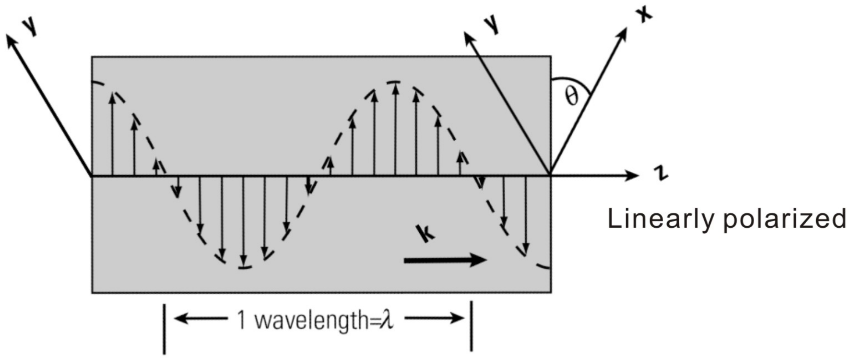
$$\boldsymbol{E} = E_x \cos(\omega t)\boldsymbol{e}_x + E_y \cos(\omega t + \Gamma)\boldsymbol{e}_y$$

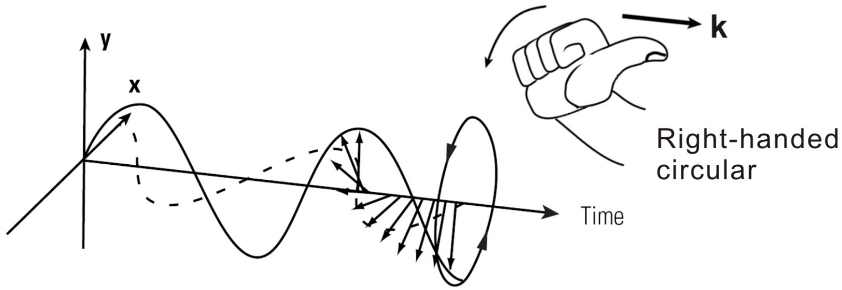
- **Linearly polarized light (G = ☒n*p*; n = 0, 1, 2,…)**

$$\tan(\theta) = E_y / E_x$$



- **Circularly polarized light (G = ☒n*p*/2; n = 1, 3, 5,)**

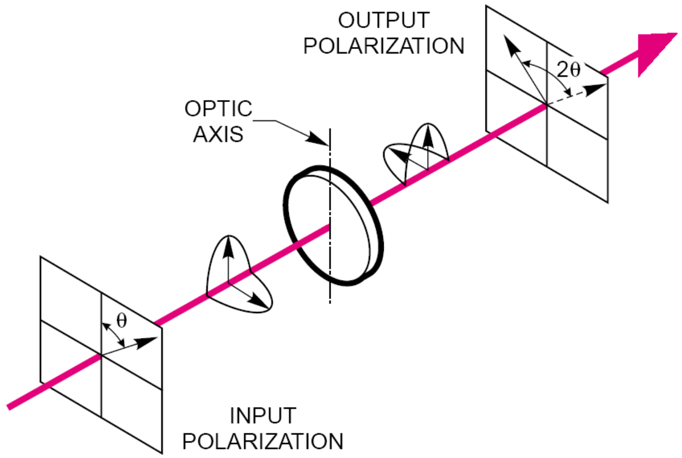
$$E_x = E_y$$



- **Elliptically polarized light**

Polarization control

- **Retarders** change the state of polarization. They resolve an incident beam of light into two orthogonally polarized components and retard the phase of one component relative to the other. The emergent beam usually has a different polarization state from the incident beam. The most common type of retarder is a slice of birefringent material in which the o-ray and e-ray travel at different velocities. Two rays which start in phase develop a phase different with respect to each other.
- After passing through the retarder, the phase of one vector component is delayed by 180° with respect to the other (a path difference of one half wavelength). The sum of the two emergent beams is a beam with linear polarization but rotated by $2q$. This retarder is also called **half-wave plate** or **polarization rotator**.



Polarization selection

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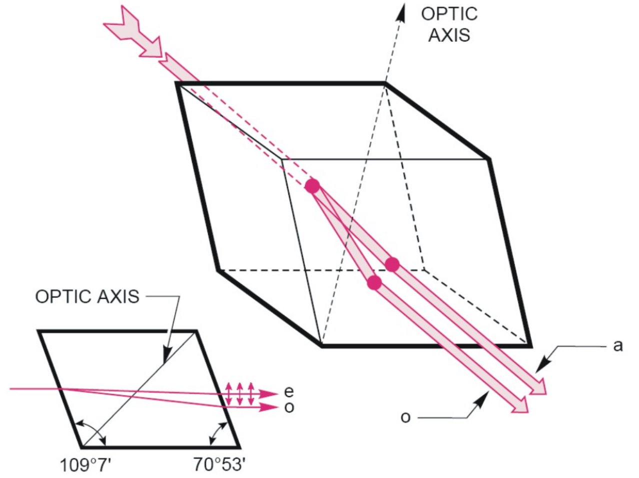
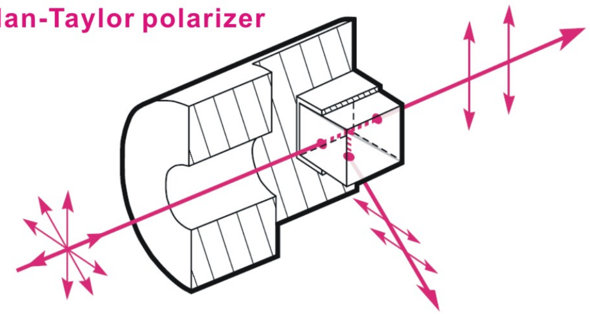
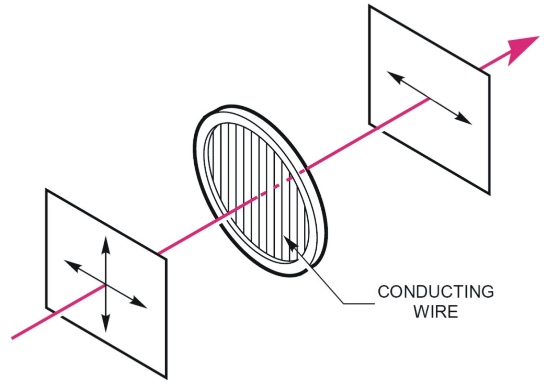
Polarization selection by double refraction



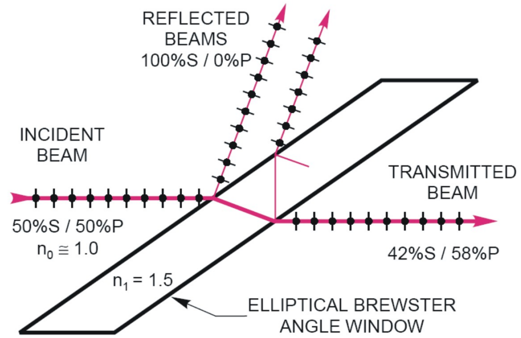
Glan-Taylor polarizer



Polarization selection by wire grid



Polarization selection by Brewster-angle reflection



Polarizer selection chart

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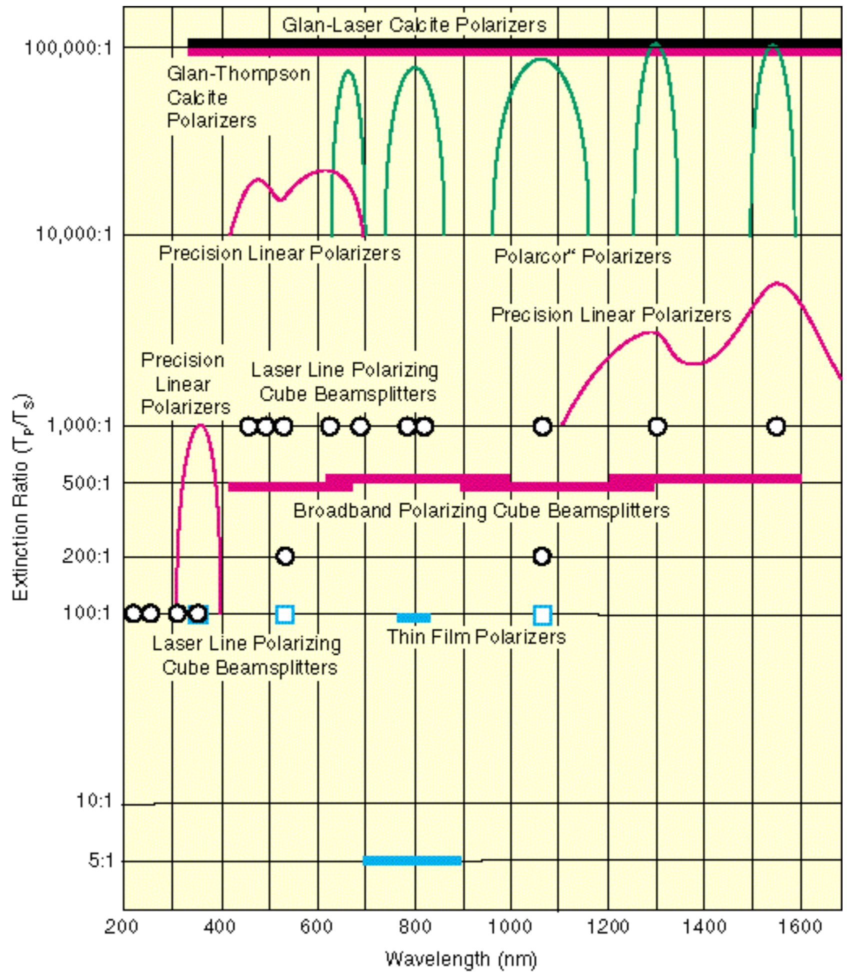
- **Wavelength coverage**: Birefringence-typed polarizers have the largest wavelength coverage range, while thin-film-typed polarizers have limited range.
- **Extinction ratio**: Birefringence-typed polarizers have the highest extinction ratio, while thin-film-typed polarizers have a small ratio.
- **Tolerance angle**: Birefringence-typed polarizers have small tolerance angle, while thin-film-typed polarizers normally have a larger angle.



Care and cleaning of optics

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- Contaminants on an optical surface increase scatter off the surface and absorb laser energy, creating hot spots that eventually lead to coating failure.
- Cleaning of any precision optic risks damaging the surface, so optics should only be cleaned when necessary.
- The need for cleaning can be minimized by returning optics to their case or covering the optic and mount with a protective bag when not in use.
- Drop and drag cleaning method is often used for light cleaning of flat optical surfaces, such as mirrors. Place the optic on a clean work surface. Blow off dust. Hold a piece of unfolded lens tissue above the optic and place a few drops of acetone on the tissue. Lower the lens tissue onto the optic and pull it across the optic. Repeat this procedure until the optic is clean. Be sure to use a new piece of lens tissue with each pass. This will avoid scratching the optical surface by dragging loose contaminants.
- Brush cleaning method is ideal for cleaning smaller optics, including lenses, and involves holding a folded lens tissue with a hemostat to brush the surface clean. Fold a lens tissue so as not to touch the part of the tissue that will make contact with the optic. The fold should be about as wide as the optic. Hold the tissue with hemostats parallel to and near the fold. While holding the optic, using tweezers if necessary, blow off any dust. Soak the tissue with acetone. Brush the fold in the tissue across the surface of the optic using light pressure. Repeat as necessary until the optic is clean, making sure new lens tissue is exposed with each wipe.

Drop-and-drag cleaning method

Brush cleaning method

Defining an optical axis-1st step

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- The most common approach to building up an optical system is to establish an arbitrary fixed optical axis and then to add components one by one, aligning each in turn to this axis. The optical axis has to be designed in advance. When working on an optical table, for example, the axis is usually designed to reside at a set height above the table, and often runs parallel to the rows of mounting holes in the tabletop.
- Optical elements that fold or offset the beam path, such as mirrors, prisms, and beamsplitters, are typically added and aligned first. When working with visible lasers, this alignment is often accomplished by steering the beam through one or more pinhole apertures that have been set mechanically to coincide with the desired optical axis. Crosshair targets can also be useful in performing this function.
- Refractive components (for example, lenses) are inserted and aligned next. The exact method used for referencing this alignment varies depending upon the type of system under construction, the characteristics (such as focal length) of the components being used, and the level of precision required. Typical techniques for aligning lenses in laser systems include the use of pinhole apertures, monitoring the position of back reflections, or closely examining the shape of the focused spot.

Lens mounting-I

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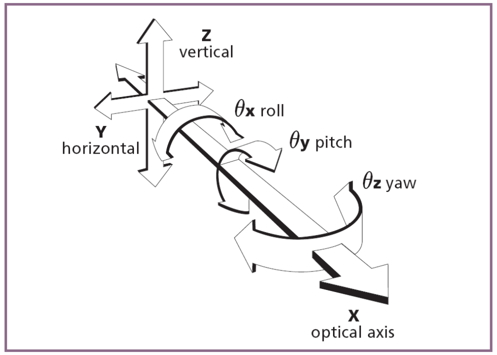
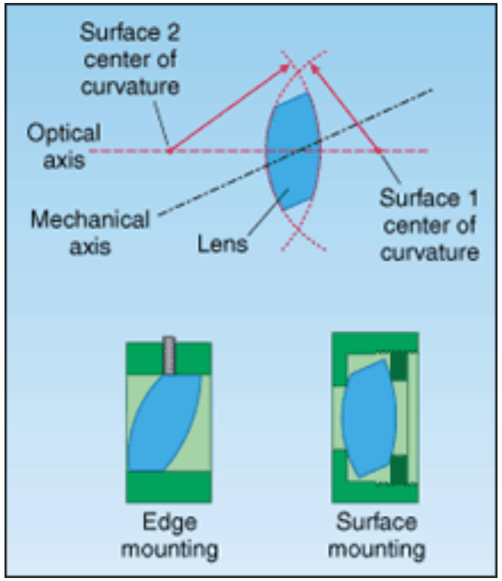
- Fixed lens holders enable coarse adjustment in z and θ_z while constraining motion in y, θ_y, x and θ_x.
- Ideally, a lens holder should retain the lens in such a way that its optical axis is automatically perpendicular to the axis of the post, to a high degree of precision.
- The optical axis of a conventional lens element with spherical surfaces is the line joining the center of curvature of each surface. The mechanical axis is defined as the geometrical axis of the cylinder formed by the edge of the lens. Centration is a measure of the separation between the optical axis and the mechanical axis of the lens.
- When a lens is held by its edge, centration errors can leave the optical axis of the lens offset or tilted relative to the mount. In contrast, a mounting scheme that is referenced to the curved surface or surfaces of the lens avoids this problem. Mounting problems related to centration are most pronounced with short-focal-length lenses, because the effect of a given offset or tilt increases with decreasing focal length.



Six degrees of freedom: X, Y, Z, θ_x, θ_y, θ_z



Lens mounting-II

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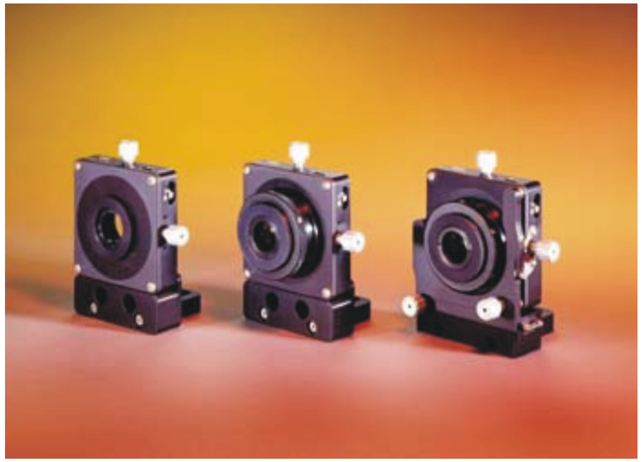
- A fixed lens holder using a single screw retainer (edge-mounting) demonstrates an extreme simplicity that yields its primary advantage—low cost. The edge-mounting approach however can introduce component tilt. A fixed lens holder using a retaining ring is a basic, workhorse optical mount that uses surface-mounting to provide adequate positioning accuracy for many optical setups.
- A self-centering lens holder is essentially a three-jawed chuck that can retain lenses over a wide range of diameters, always locating the center of the lens at the same position. This is the most useful type of lens holder to hold different lenses. The main disadvantages of this mount design are its high cost and the use of edge-mounting.
- Adding *y*-*z* adjustment to a retaining-ring lens holder yields a translating lens holder, which can achieve precise positioning, yet remains very compact. This type of mount provides adequate positioning functionality and resolution for the vast majority of applications.
- Adding *x* adjustment makes focusing adjustment easy, while Extra θ_y and θ_z adjustment enable further fine adjustment on lens tilting with respect to the optical axis.

Fixed lens mount

Adjustable lens mount



2-axis 3-axis 5-axis

Lens positioners

Mirror mounting-I

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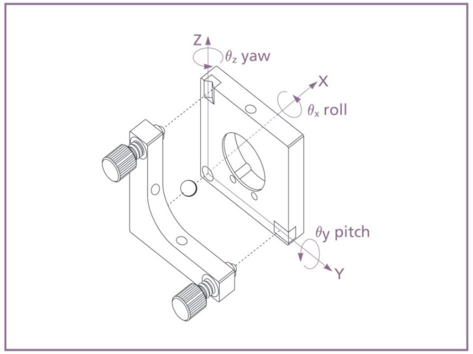
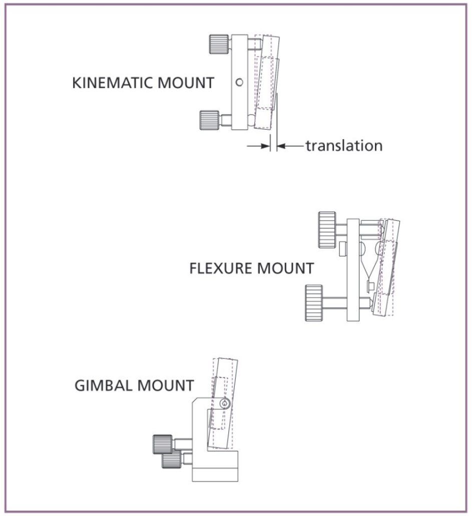
- The majority of all opto-mechanical components are made from aluminum, brass, or stainless steel. All relevant material properties should be considered.
- Stiffness (Young's modulus) is a measure of the amount of stress (force/area) required to cause a given amount of strain (normalized deformation). Stainless steel is approximately three times stiffer than that of aluminum. Components with the same shape and specific stiffness (Young's modulus divided by the material density) will have the same fundamental resonant frequencies. Higher specific stiffness results in higher resonant frequencies, faster settling times, and a reduction in vibration disturbances.
- The thermal expansion of stainless steel is roughly half that of aluminum. This is important for an application requiring interferometric stability. The thermal conductivity of aluminum is ten times greater than that of stainless steel so heat can be dissipated more readily, thus reducing the thermal gradients and distortion.
- When selecting optical mounts, the user should ensure that the mounts can interface with the dimensions of all the various types of optics in use (for example, diameters, thicknesses or shapes), and that the mechanical interface is flexible enough to enable a wide variety of configurations to be constructed.



Kinematic mount with a cone, groove, and flat



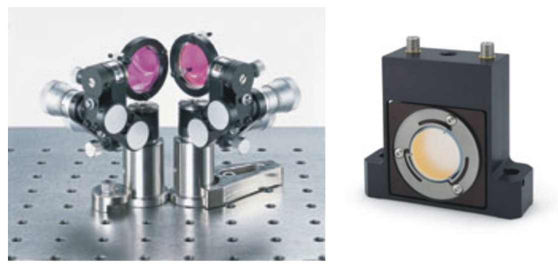
Kinematic, flexure, and gimbal mounts

Mirror mounting-II

- In a kinematic mounts, the mirror is mounted on a movable plate, the angle of which is changed relative to a fixed plate by use of two adjustment screws at opposite corners. The plate is preloaded (pulled) against these screws and a fixed ball-bearing by a single coil spring. The design of kinematic mounts inherently limits their angular range of adjustment to around 5° to 10°.
- The kinematic mounts which do not use very stiff springs limit resolution and repeatability. It can also allow the mount to sag under heavy loads. Another intrinsic problem is that their center of rotation is not at the surface of the mirror producing a translation in the reflected beam during an angular adjustment. These problems necessitate several adjustment iterations to align a system consisting of two or more kinematic mounts.
- The axes of rotation for gimbal mounts are orthogonal, non-interacting, stationary, and centered on the optic. Moreover, a gimbal mount, if properly constructed, can deliver the ultimate in range, resolution, repeatability and stability. Some more sophisticated products have both high resolution and full 360° travel in both axes.

Kinematic mounts

Gimbal mounts



Special mounts

Architectural components

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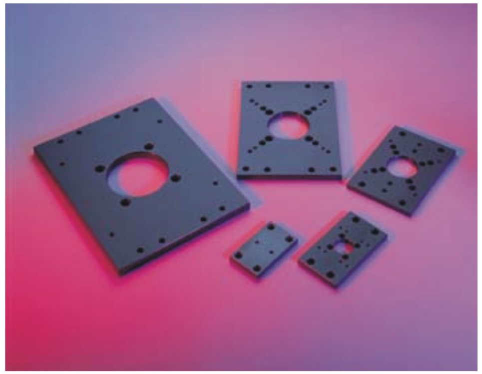
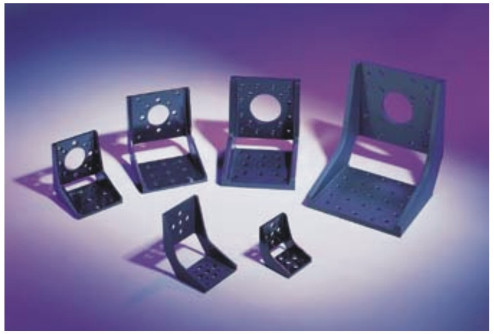
Post & post holder

Pedestal post & clamp



Base

Rail & carrier



Angle bracket

Magnetic base

Read specification-I

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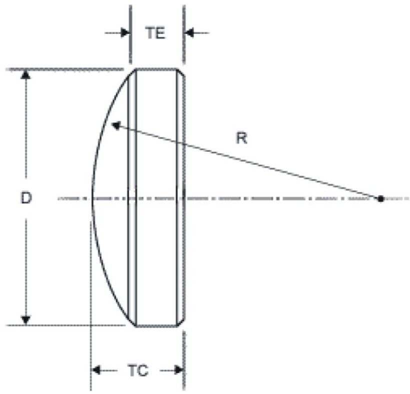
Singlet spherical plano-convex lens



Specifications	
Substrate Material	BK7 glass
Surface Figure	λ/10 at 633nm typical
Surface Quality	10-5 laser quality
Dimensional Tolerance	+ 0.00mm, - 0.25mm
Thickness Tolerance	± 0.25mm
Chamfer	0.35mm at 45° typical
Concentricity	≤0.05mm
Focal Length Tolerance	± 0.5% typical
Antireflection Coating	User specified, R ≤0.25% per surface
Clear Aperture	Exceeds central 85% of dimension
Damage Threshold	10J/cm^2, 8nsec pulse; 1MW/cm^2, CW at 1064nm typical

Lens Part Number	Nominal f (mm)	Diameter D (mm)	532 nm f (mm)	633 nm f (mm)	1064nm f (mm)	1319 nm f (mm)	Radius R (mm)	TC (mm)	TE (mm)
***********	100	25.4	99.1	100	101.7	102.3	51.5	4	2.4

Read specification-II

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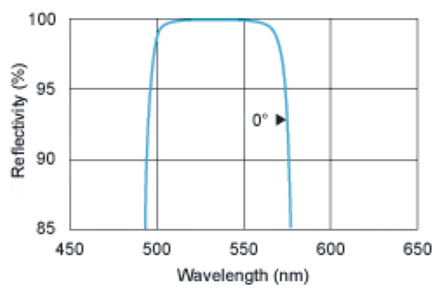
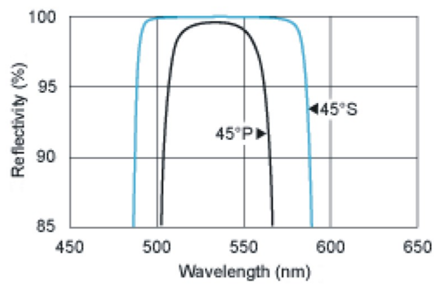
Nd:YAG laser mirror





Reflectivity vs. Wavelength of 532nm Nd:YAG Laser Mirror at 0° and 45° incidence angles.

Specifications	
Substrate Material	BK7 glass
S1 Surface Figure	λ/10 typical at 633nm
S1 Surface Quality	10-5 laser quality
S2 Surface Quality	Commercial polish
Diameter Tolerance	+ 0.00mm, - 0.25mm
Thickness Tolerance	± 0.25mm
Wedge	≤5 minutes
Chamfer	0.35mm at 45° typical
Concentricity	≤0.05mm
Radius Tolerance	± 0.5%
Coating Technology	Electron beam multilayer dielectric
Adhesion and Durability	Per MIL-C-675C. Insoluble in lab solvents.
Clear Aperture	Exceeds central 85% of diameter
Damage Threshold	20J/cm^2, 8nsec pulse; 1MWcm^2, CW at 1064nm typical. Contact CVI for damage certification up to 40J/cm^2.
Coated Surface Figure	λ/10 at 633nm over 85% of diameter available

Read drawing

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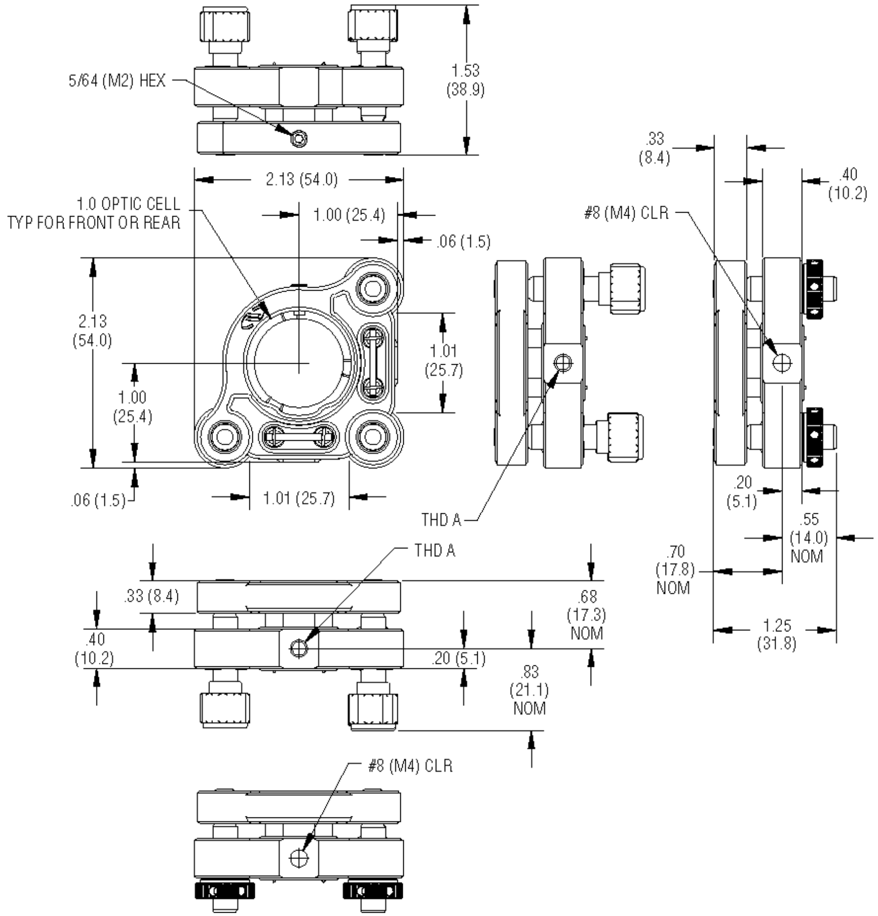
Kinematic mirror mount



Twyman-Green interferometer

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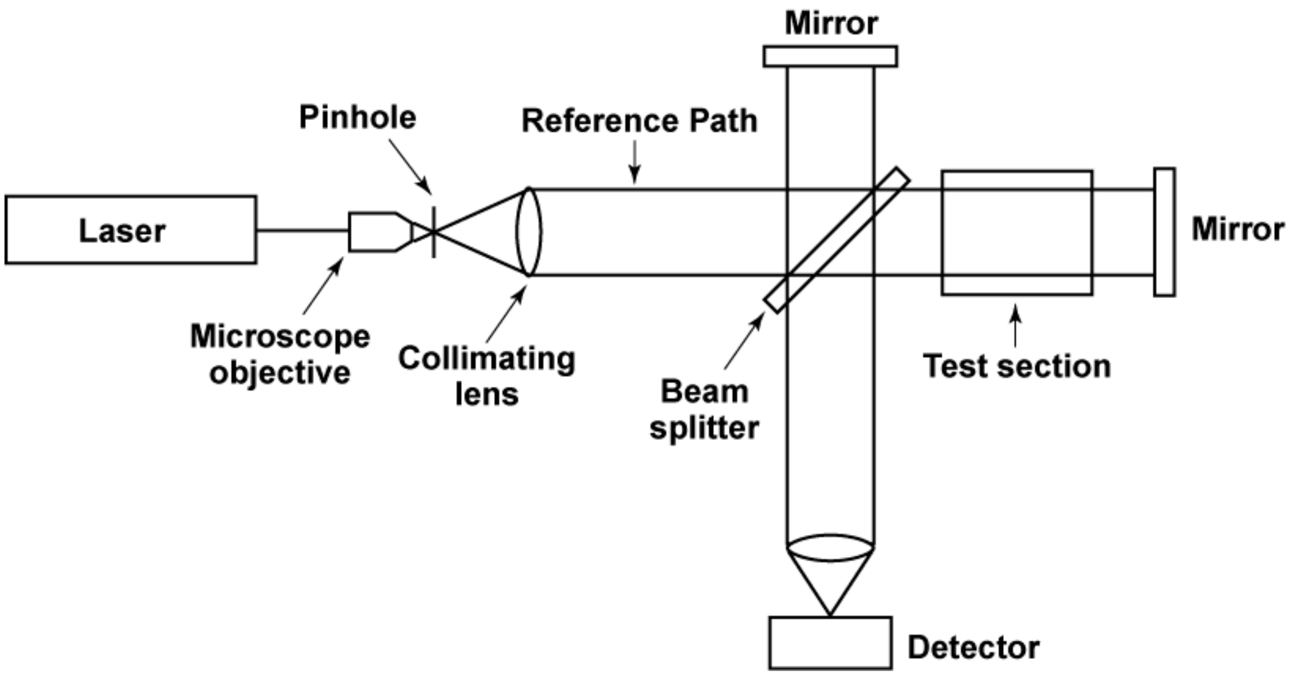
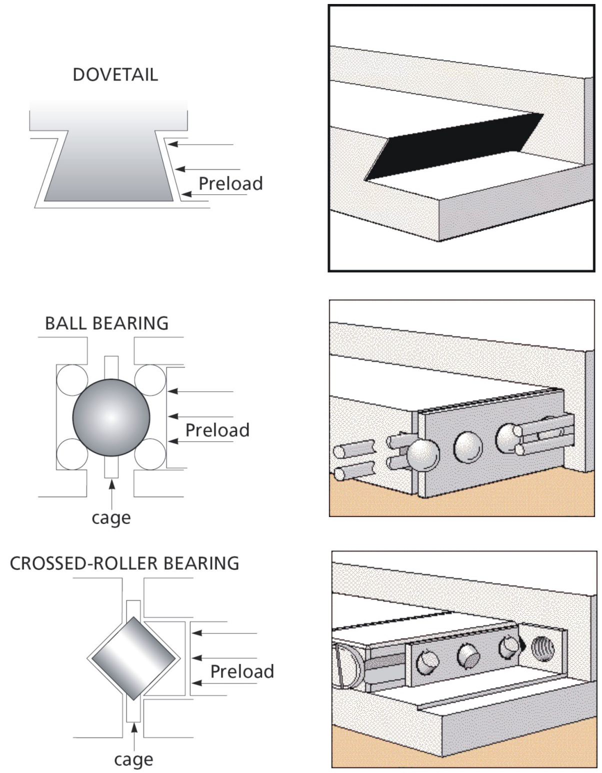


- Twyman-Green interferometer is a modification of Michelson interferometer used to test optical components. After the laser light is collimated by a microscope objective and a collimating lens, the collimated beam is divided into two beams of equal intensity by a 50/50 beam splitter. After reflection, light from both mirrors impringes again on the beam splitter. An interference pattern is then formed at the detector site.
- In this course, every student is required to perform a hand-on experiment on setting up a Twyman-Green interferometer to measure the refractive index of an unknown right-angle prism.

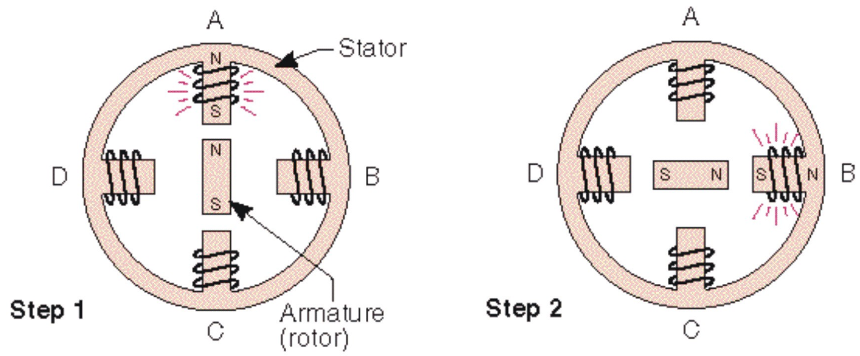
Bearings

- Dovetail slides is very simple and effective in systems requiring long travel. They are usually chosen for low-cost systems with infrequent motion. They are seldom appropriate for high-precision systems because of their high friction and stiction (breakaway friction). Stiction limits positional resolution and also provides a means whereby stored residual stress can be spontaneously released, causing creep and drift.
- Ball bearing stages replace the friction of sliding motion used in dovetail slides by a lower friction rolling motion. A linear array of spherical balls is held between V-grooves or rails with a cage that prevents adjacent balls from touching one another. Bearings require lubrication to prevent seizing and reduce friction and stiction.
- Crossed-roller bearing stages replace balls with small steel rollers. By having the axis of rotation alternate or cross at 90 degrees, the stage can be preloaded and will operate at any angle. Point loading of the ball bearing is changed to a line contact with the roller bearing. Thus, because of the larger load-bearing surfaces (line rather than point), crossed-roller bearings can have a higher preload applied, carry greater loads, and meet very tight runout specifications.

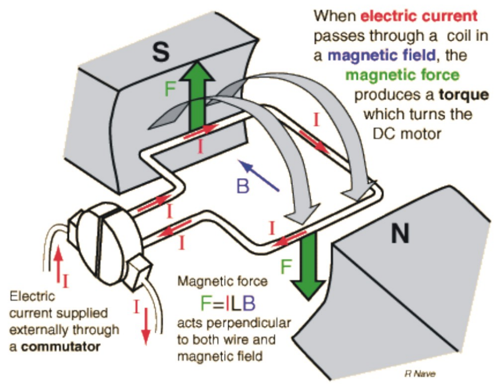


Motors and Encoders

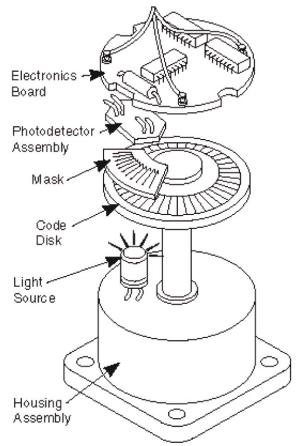
- A **stepping motor** operates using the basic principle of magnetic attraction and repulsion. Steppers convert digital pulses into mechanical shaft rotation. The amount of rotation is directly proportional to the number of input pulses generated. When a stepping motor at rest, a full-step motor's stop position does not drift.
- A DC motor essentially consists of a rotor placed in a magnetic field which causes rotation when current is applied to the motor windings. DC motors are best characterized by their smooth motion and high speeds. Unlike stepper motors, DC servo motors do not provide full torque when idle. Precise closed-loop servo positioning and speed control is typically achieved with a shaft-mounted rotary encoder.
- **Rotary and linear optical encoders** are used frequently for motion and position sensing. A disc or a plate containing opaque and transparent segments passes between a light source (such as an LED) and detector to interrupt a light beam. The electronic signals generated are then fed into the controller where position and velocity information is calculated based upon the signals received.



Stepping motor action



DC motor operation



Rotary encoder

Manual and motorized drives

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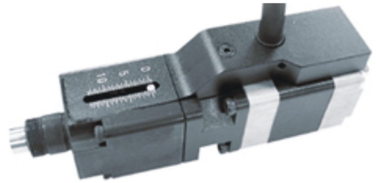
Adjustment screw

Micrometer

Differential micrometer

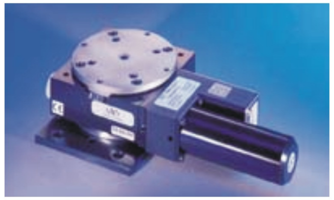
Piezo actuator

DC motor drive

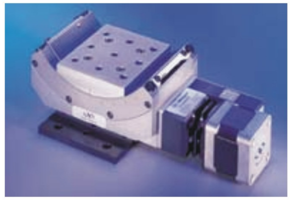


Stepping motor drive

Motorized
translation stage



Motorized
Rotation stage



Motorized
Goniometric stage

Piezoelectric effect

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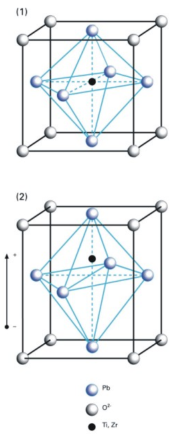
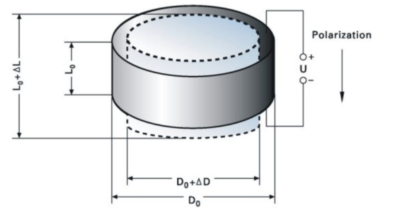
- The application of an electric field to a piezoelectric crystal (such as PZT) leads to a physical deformation, which is called **piezo-electric effect**. The deformation is proportional to the applied electric field.
- When the operating temperature is raised above **Curie temperature**, the electric dipoles are randomly arranged while being subjected to an electric field. During this process, the electric dipoles align and respond collectively to subsequent smaller field changes .
- The active part of the positioning element consists of a **stack of ceramic disks** separated by thin metallic electrodes. The maximum operating voltage is proportional to the thickness of the disks. The stack actuators are usually manufactured with layers from 0.02 to 1 mm thickness. Displacement of a PZT stack actuator can be estimated by the following equation:

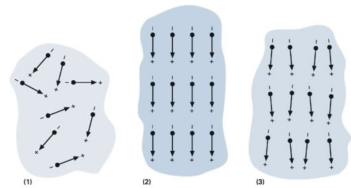
$$\Delta L \approx d_{zz} \cdot n \cdot V$$

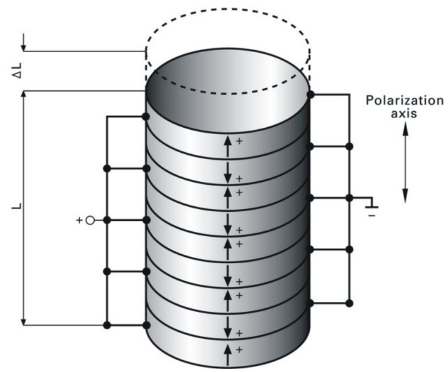


Perovskite-type lead zirconate titanate (PZT)



Elongation and contraction of a PZT disk when a voltage is applied


Electric dipoles in domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling



Electrical connection of disks in a PZT stack actuator which elongates the travel range

Considerations in Piezo positioners

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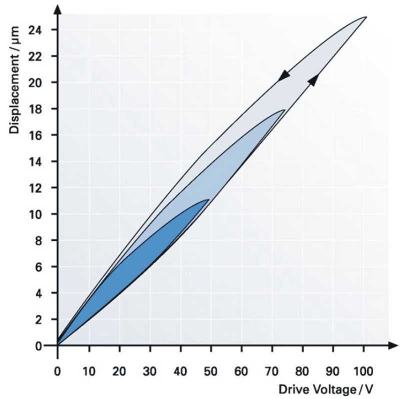
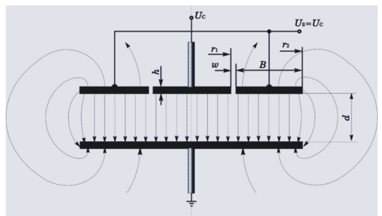
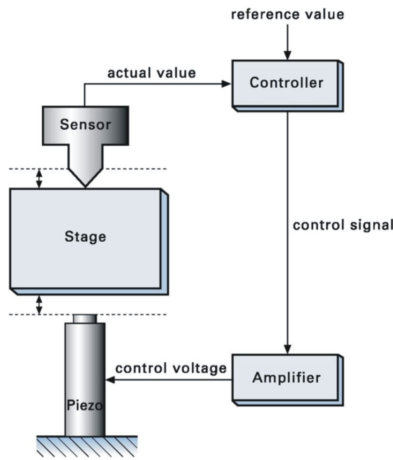
- Similar to electromagnetic devices, open-loop piezo actuators exhibit **hysteresis**. The absolute displacement generated by an open-loop PZT depends on the **applied voltage** and the **piezo gain**, which is related to the remanent polarization. Since the remanent polarization, and therefore the piezo gain, is affected by the electric field applied to the piezo, the deflection depends on whether the PZT was previously operated at a higher or a lower field strength. Besides hysteresis, open-loop pieozo actuators also exhibit creep which is the expression of the slow realignment of the crystal domains in a constant electric field over time. When a voltage is just applied, the remanent polarization continues to change, manifesting itself in a slow creep.
- **Closed-loop PZT actuators** are equipped with position measuring systems (such as **capacitive position sensors**) providing sub-nanometer resolution and bandwidths up to 10 kHz. A servo-controller determines the output voltage to the PZT by comparing a reference signal (commanded position) to the actual sensor position signal and is the key to highly repeatable nanometric motion.



Hysteresis curves of an open-loop piezo actuator for variousvoltages



Capacitive position sensors



Closed-loop position control of a stage driven by a piezo actuator

Piezoelectric positioners

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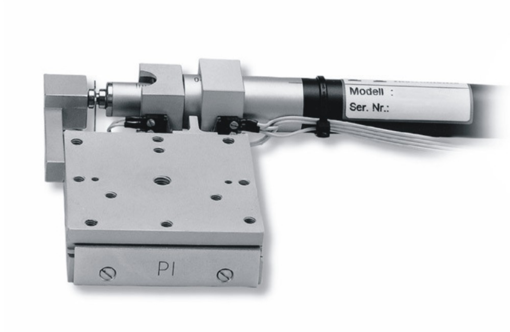
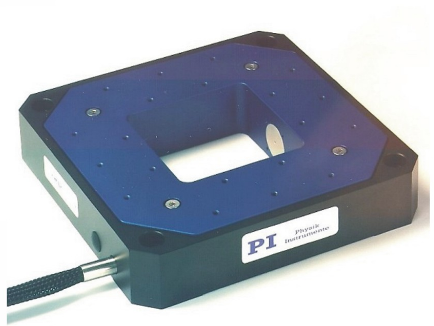
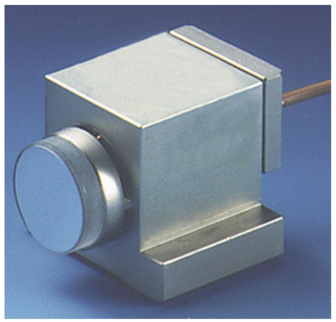
Objective positioner



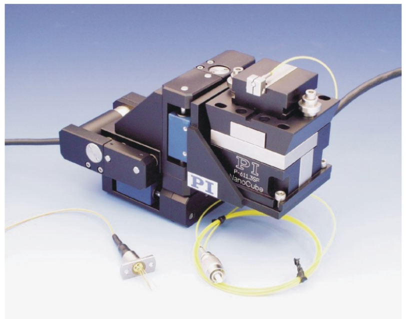
Piezo linear motor actuator



Nanopositioning platform



Tilt platform



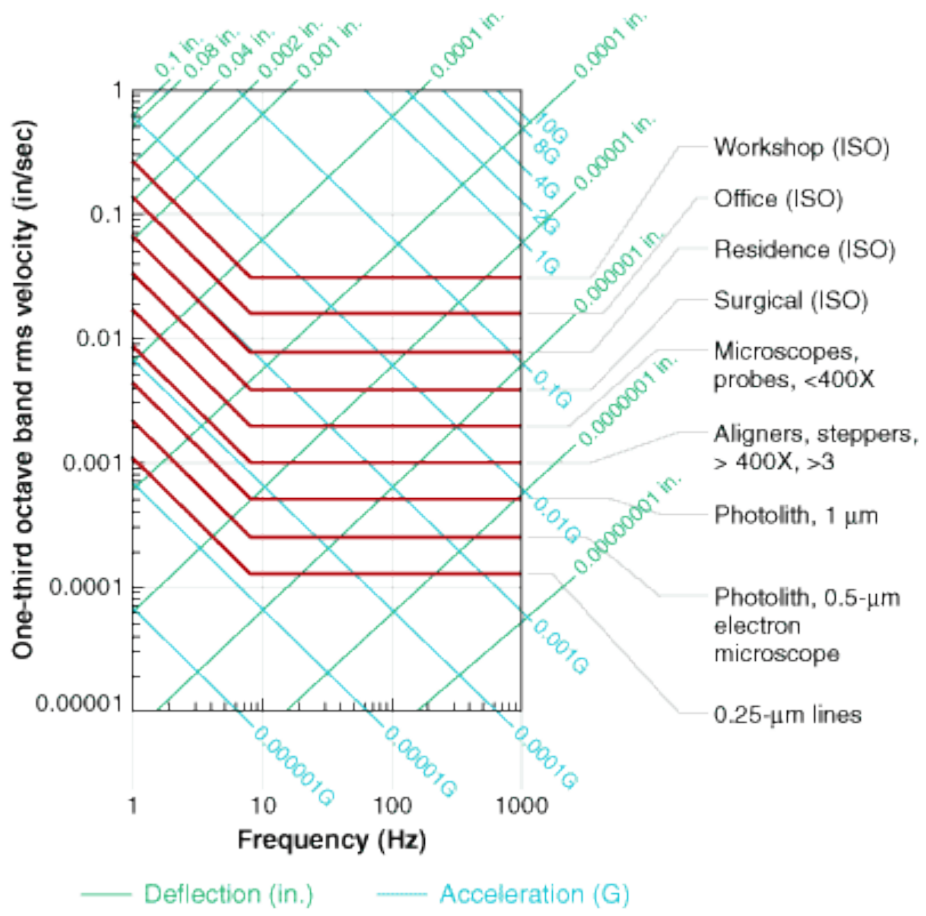
Piezo fiber alignment system

Nano scanning stage

Why vibration-isolated optical table?

Dr. Juen-Kai Wang, CCMS & IAMS

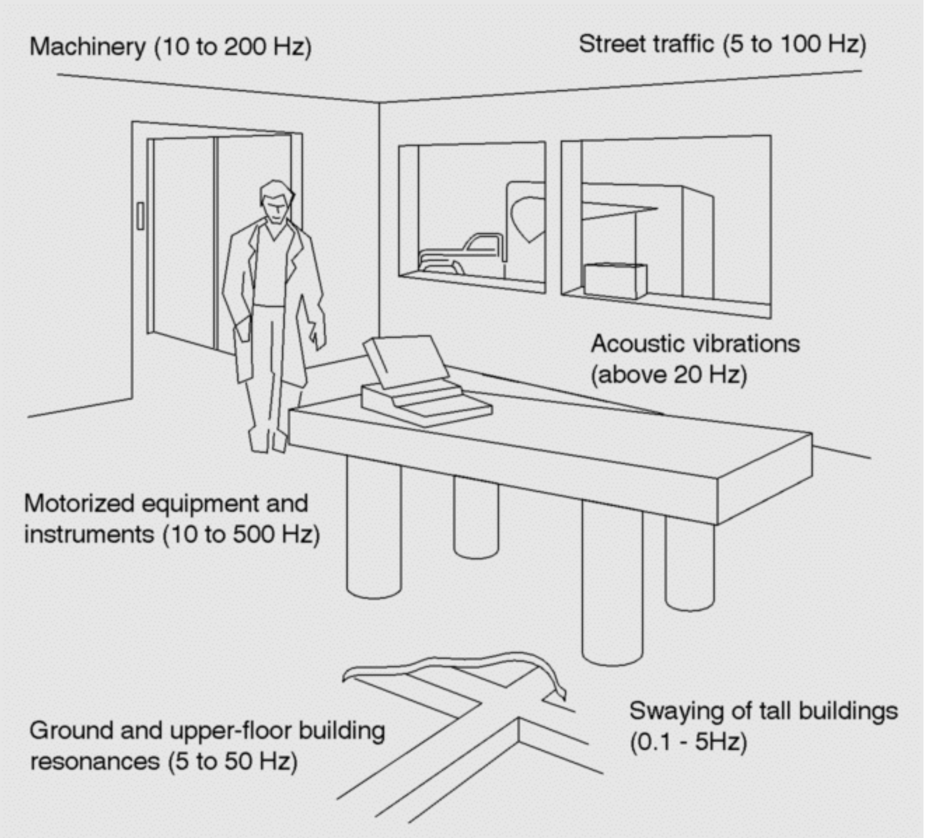
- To eliminate relative motion between position sensitive components across the table work surface
- To filter floor vibration before it can reach the table top and disturb an optical beam path
- To rigidly resist deflection from moving loads or any vibration that passes through the isolation system



Common instability sources in lab

Dr. Juen-Kai Wang, CCMS & IAMS

- Vibration, thermal changes, and static and dynamic loading can skew the results of scientific experiments or reduce the resolution and accuracy of sensitive instrumentation.
- No vibration control system can completely eliminate these sources of instability, but the better the vibration control you have under your equipment, the better it will perform.



Some of the common sources of system instability in a "quiet" laboratory environment

Five important lessons

Dr. Juen-Kai Wang, CCMS & IAMS

- To control the effects of vibration:
  - Connect all of the critical elements together in a dynamically rigid structure that is designed to eliminate (damp) structural resonances.
  - Isolate the system from vibration.
- To control the effects of static forces:
  - Build a statically rigid structure that deforms as little as possible with the application of external forces, such as a heavy table load.
- To control the effects of temperature changes:
  - Control the environment to reduce temperature variation. For example, avoid placing heat-generating equipment below the table, and insulate equipment and hardware from heat sources like lamps or flames.
  - Design the table top to be as insensitive to temperature as possible. For extremely critical applications, however, it may be necessary to specify materials which do not change physical dimension with changes in the temperature. An example is Super Invar, a material with a very low coefficient of thermal expansion.

Key components in vibration isolation

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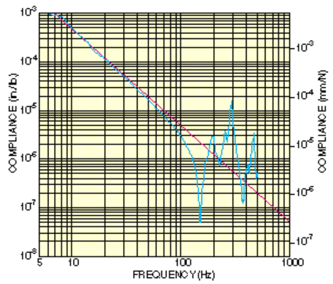
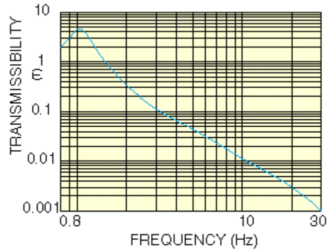
Tables provide a rigid platform



Compliance curve describes dynamic rigidity

Isolators provide mechanical filtering



Transmissibility curve describes filtering

Compliance curve

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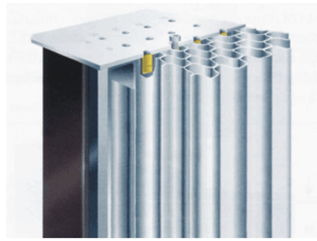
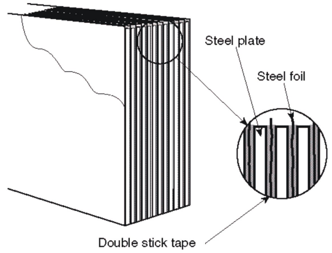
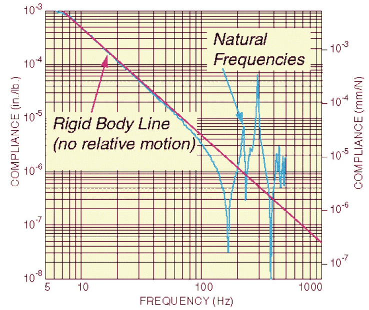
- Compliance curve shows the dynamic response of the table top in a free space condition—in other words, it gives an indication of how the surface will change shape in response to vibration. Compliance curves are transfer function curves which show the position response of a point on the table surface to a time variant force applied at the same point.
- Beginning at 0 Hz the curve slopes downward without discontinuities until several hundred Hz. Throughout this region the optical table is rigid and exhibits no relative motion across the surface. The peaks at higher frequencies represent the amplitudes of the natural modes of the table.
- The compliance curve also gives information about the damping built into the structure. Damping reduces the amplitude of the relative motion across the table work surface. In general, honeycomb structures have more inherent damping than granite structures.
- Narrowband damping techniques can virtually eliminate a natural mode (or modes) altogether. For a damped table, the compliance curves exhibit rounder, less prevalent discontinuities.



Honeycomb structure



Damped tuner



Transmissibility curve

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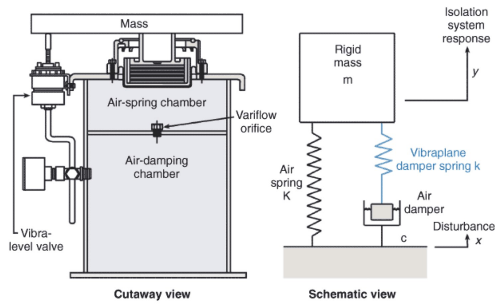
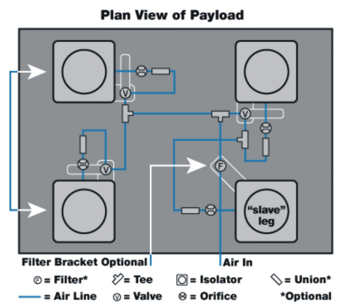
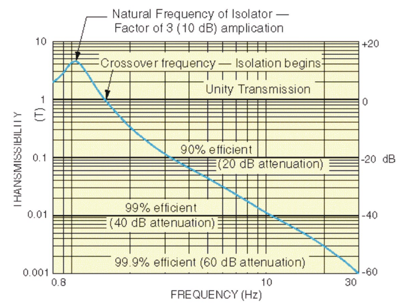
- Transmissibility curve shows the mechanical filtering properties for the isolator leg—in other words, it gives an indication of how much floor vibration will be transmitted through the leg to the table top. It is a relative measure given as a ratio of vibration at two points; one on the top of the isolator and one on the floor. The curve rises and peaks at 1–2 Hz (the natural frequency of the isolator). The peak signifies the maximum amplification of the isolator design. Lightly damped isolators will exhibit a tall, sharp peak; heavily damped isolators will exhibit a lower amplitude, rounder peak.
- Workstations are available with auto-leveling devices, usually connected to a compressor or other pressurized air source. Using servo valves to feed air to or bleed air from each table leg, the tabletop is maintained at a preset zero-deflection level independent of load addition or removal.
- An active vibration isolation system, at low frequencies, gives extra -20 dB of isolation at 2 Hz. The principal applications which were sensitive at low frequencies—less than 10 Hz—are Scanning Probe Microscopes.







Useful characteristics of laser

Dr. Juen-Kai Wang, CCMS & IAMS

- **Intensity**
  Nowadays, the laser intensity can reach more than 10^{21} W/cm^2. For reference, the damage threshold for retina is 10^6 W/cm^2. Many new physical phenomena (such as relativistic QED) can thus be discovered.
- **Monochromaticity**
  The linewidth of a CW single-mode laser can reach less than 100 kHz (~3×10^{-6} cm^{-1}, ~4×10^{-10} eV, ~2×10^{-7} nm @800 nm). It can be used to perform experiments (such as gravitational wave, quantum computing) with extremely high spectroscopic precision
- **Directionality**
  The beam divergence angle of a commercial Ar-ion laser can be less than 1 mrad (~0.057°). A laser beam will be only expanded to 250 km if it is sent from earth to moon (separated by 384,400 km). Long-distance metrology (such as earthquake and volcano monitoring) is then possible.
- **Coherence**
  The phase oscillation of a CW single-mode laser can maintain for more than 300 km, making 3D holography and high-precision surface metrology possible.
- **Time-precision**
  Hundreds attosecond pulses (1 as = 10^{-18} sec) can be produced presently. Many ultrafast phenomena in physics, chemistry and biology can then be studied.

Common wavelengths of laser

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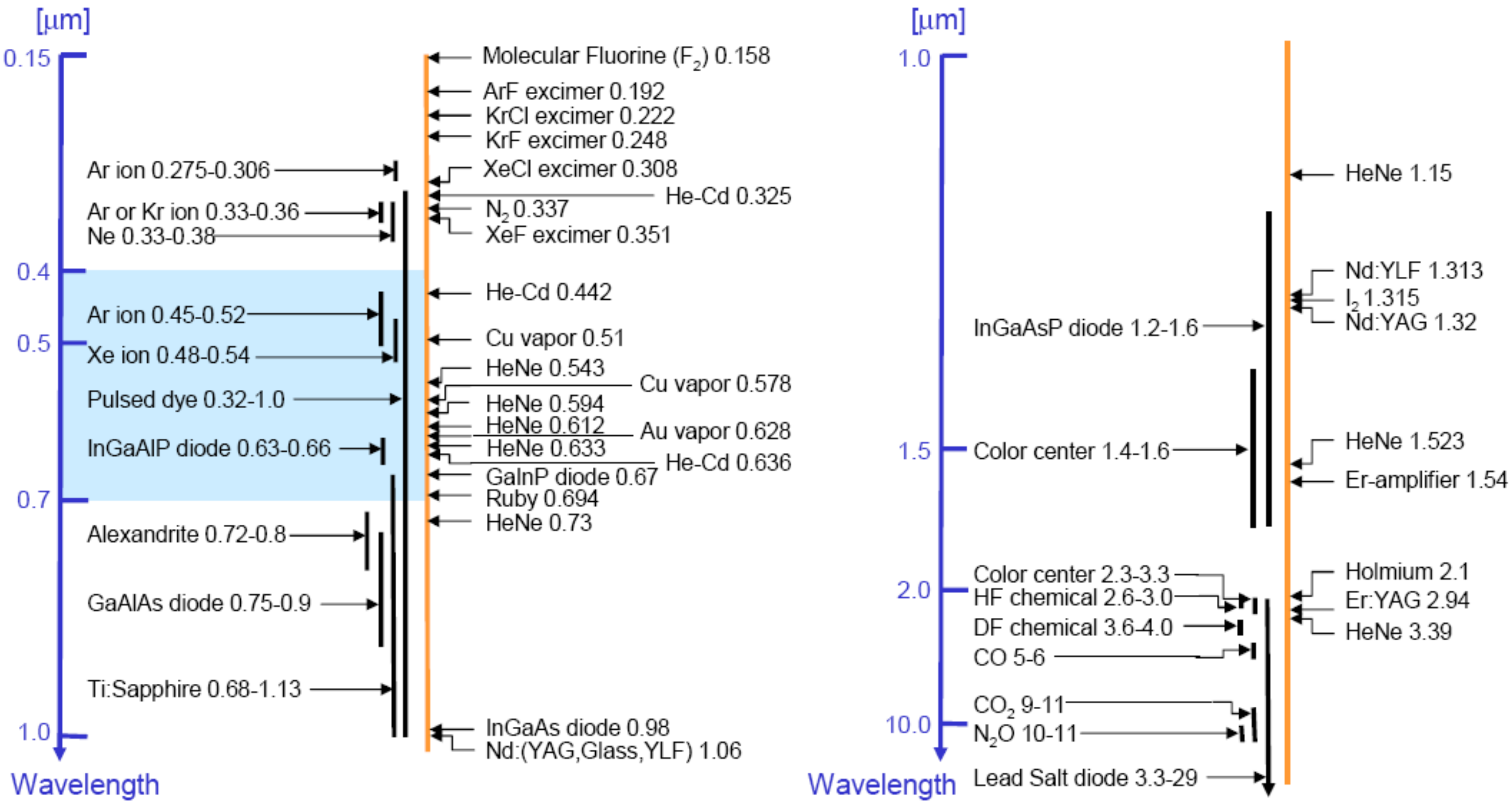

Ted Maiman's ruby laser (1960)

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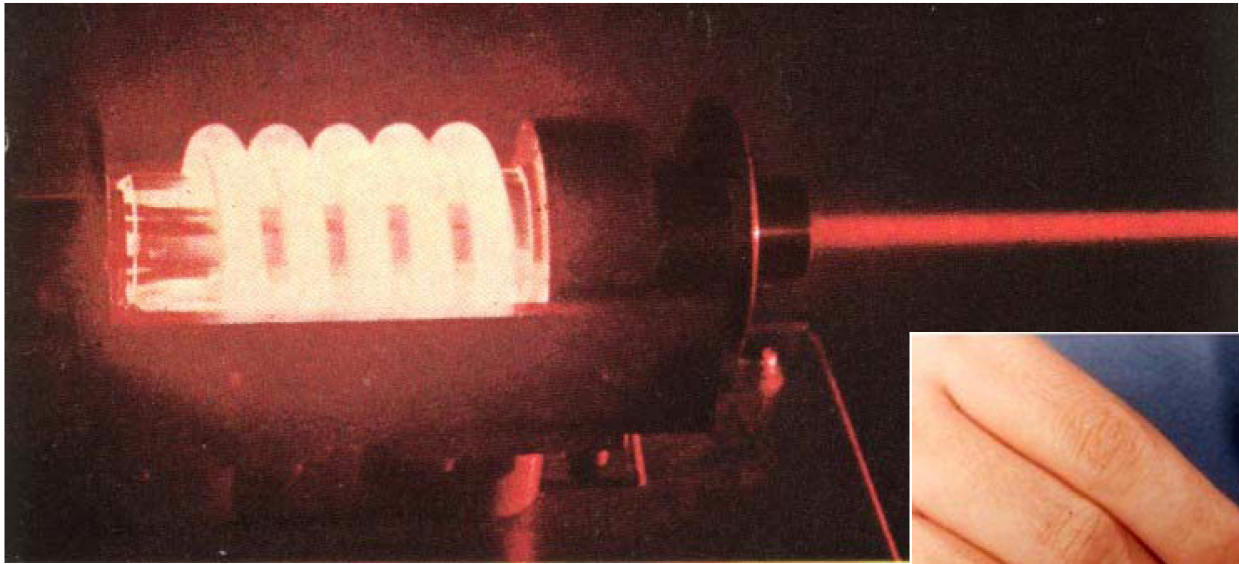

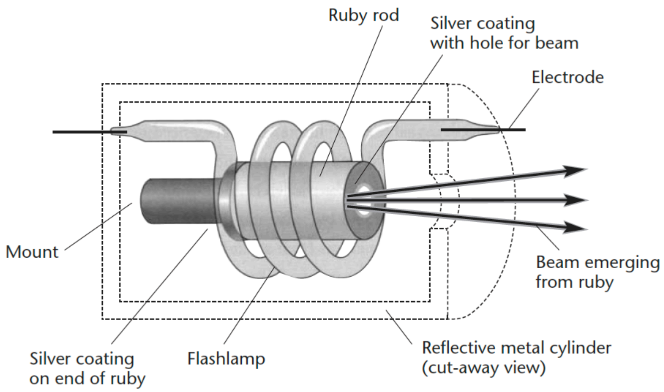

Structure of Maiman's first laser.

Key components of laser

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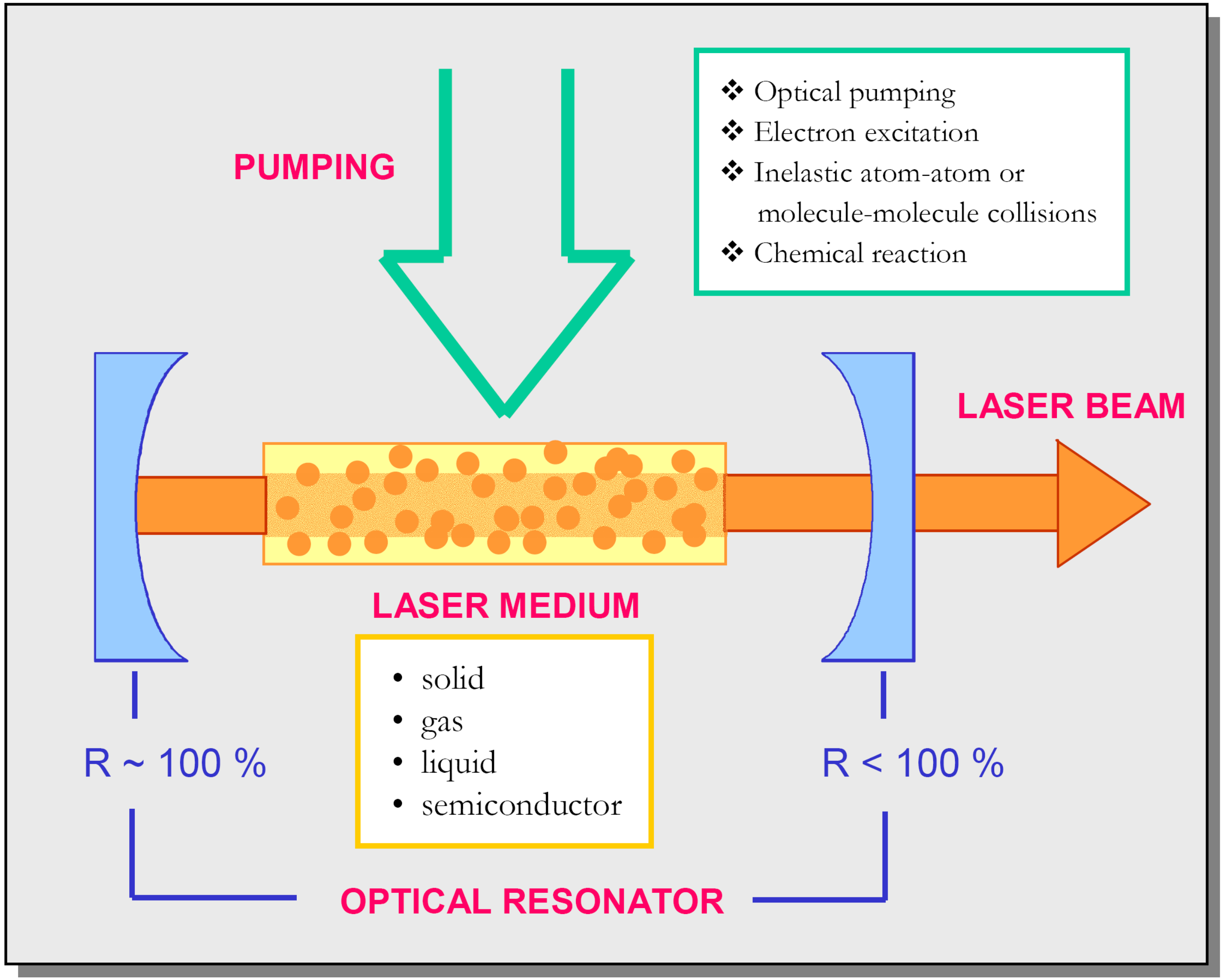

Laser resonator cavity

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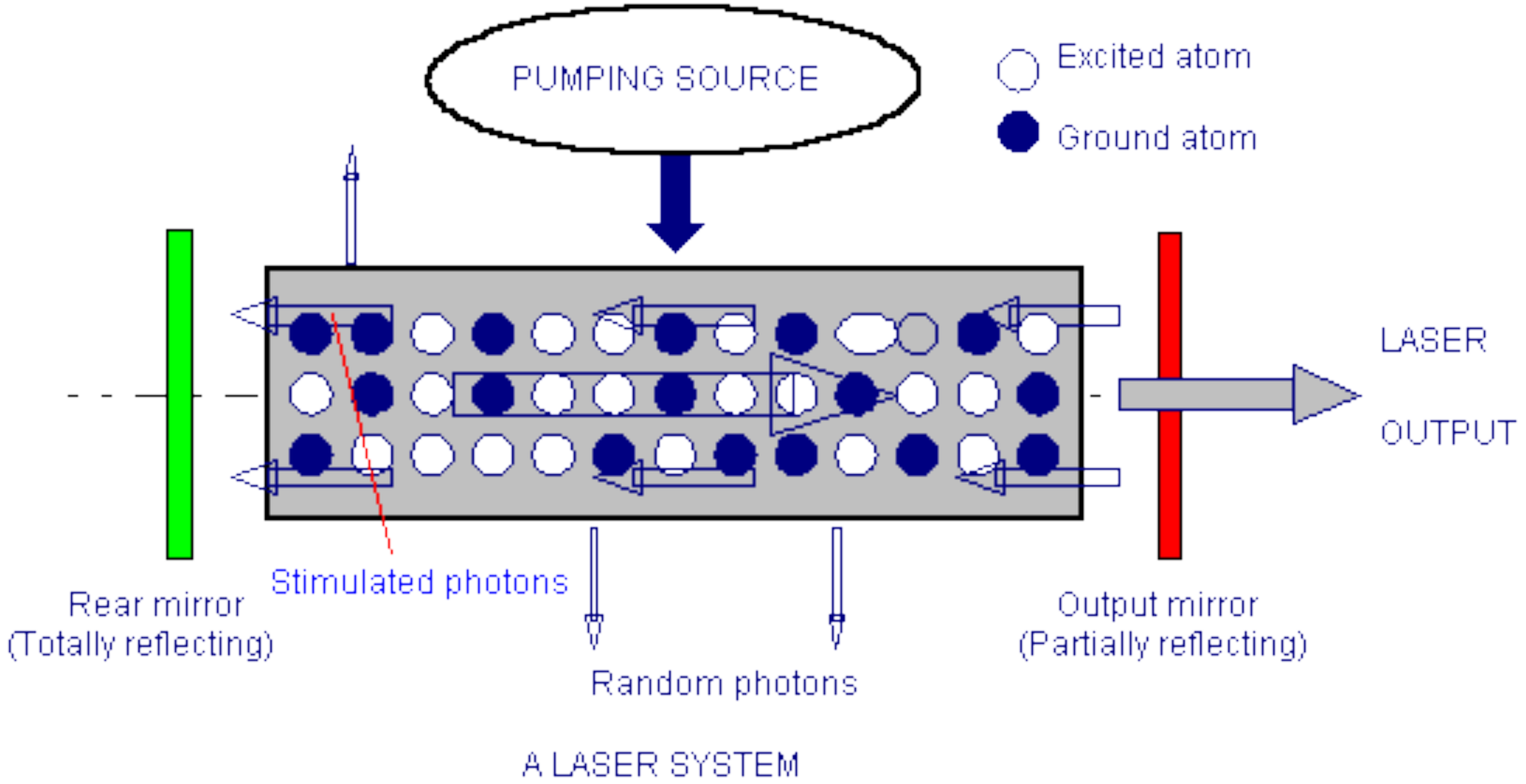

Laser modes

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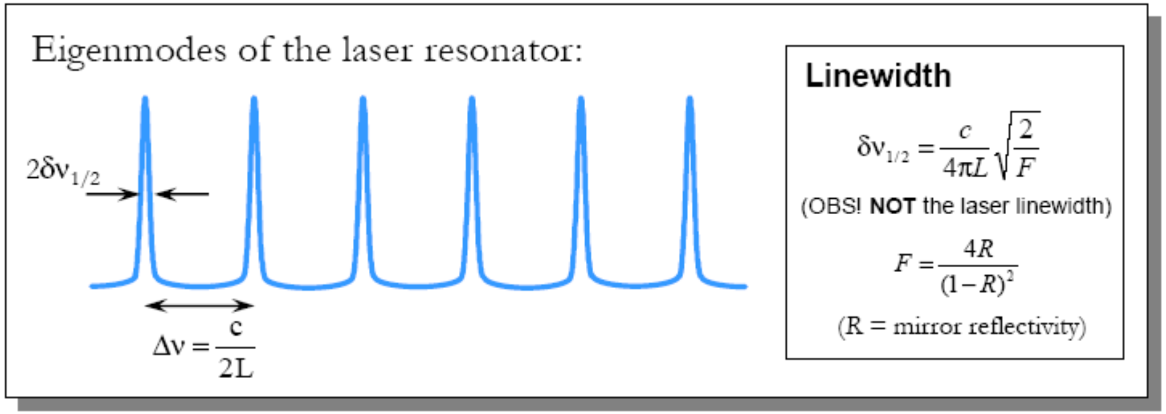
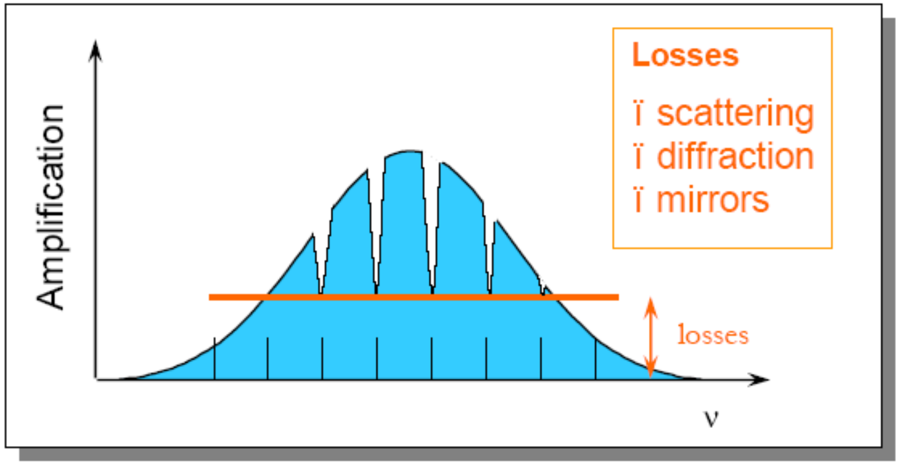
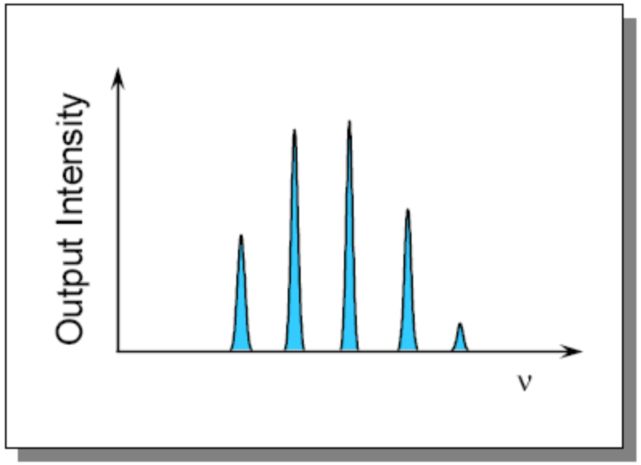
AMPLIFYING MEDIUM placed in OPTICAL RESONATOR ⇒ LASER







Spectral hole burning

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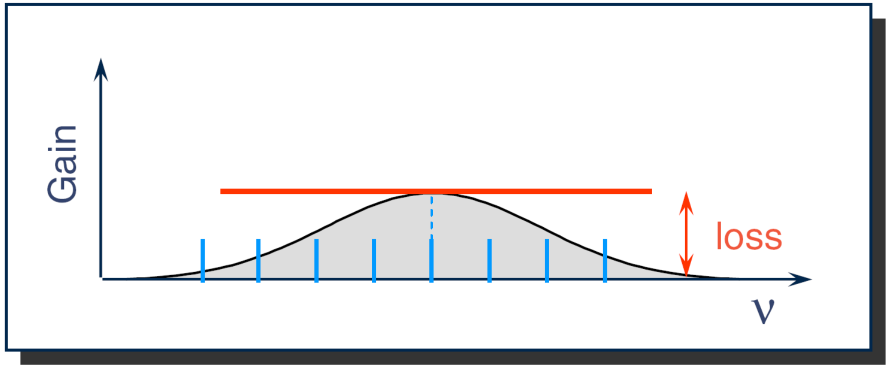
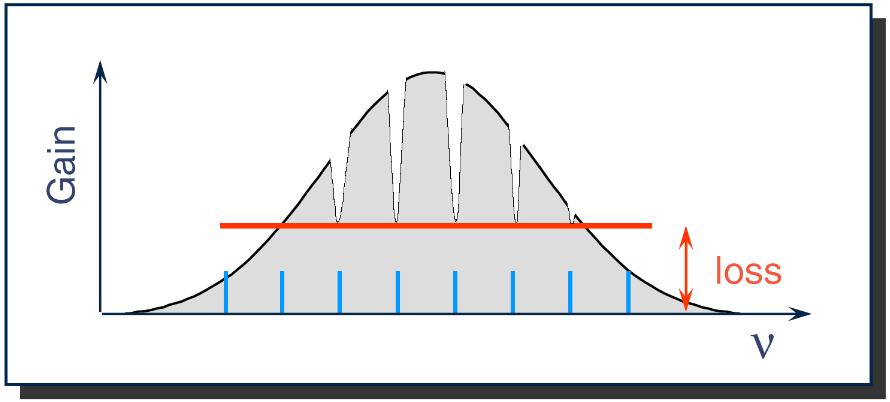
homogeneously broadened laser



single longitudinal mode
”survival of the fittest”

inhomogeneously broadened laser



multiple longitudinal modes
”spectral hole burning”

Single-mode laser

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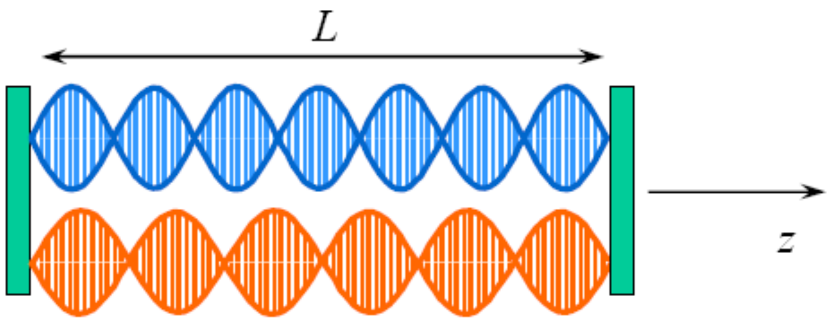
LONGITUDINAL MODE

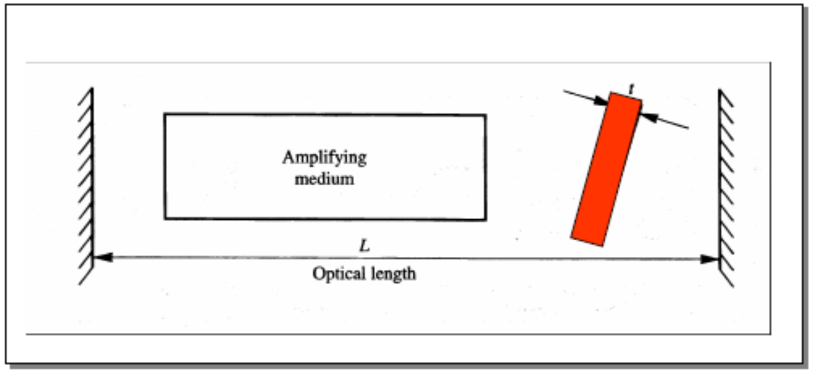
$$L = m \cdot \frac{\lambda}{2}, \quad m = \text{integer}$$

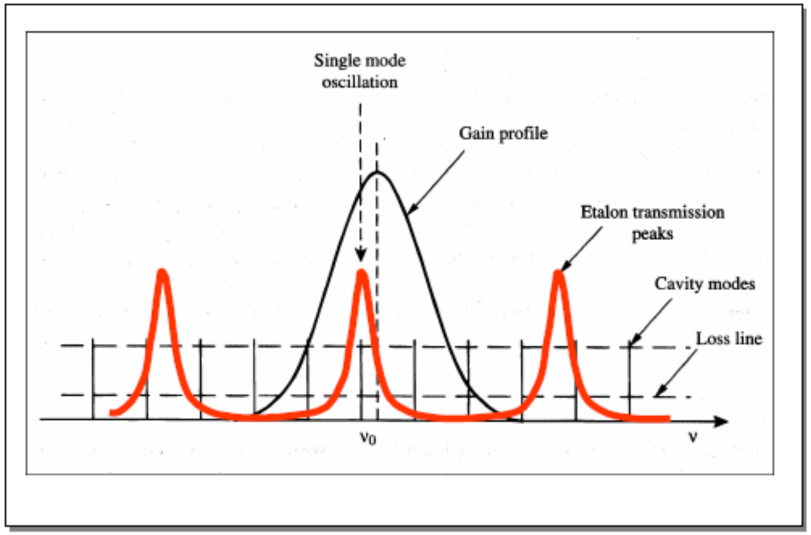


$$\lambda = \frac{2L}{7}$$

$$\lambda = \frac{2L}{6}$$

SINGLE LONGITUDINAL MODE OPERATION





Laser wavelength tuning

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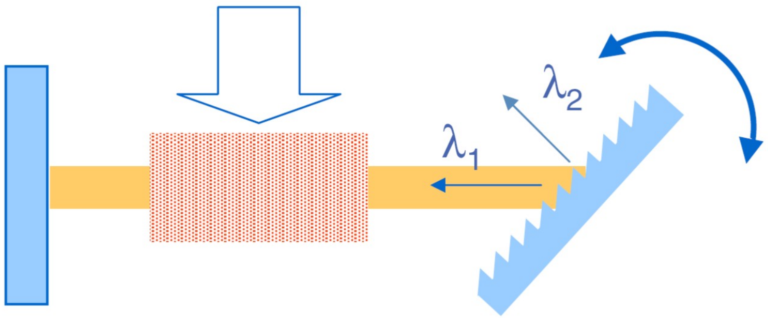
Some lasers have a broad gain profile

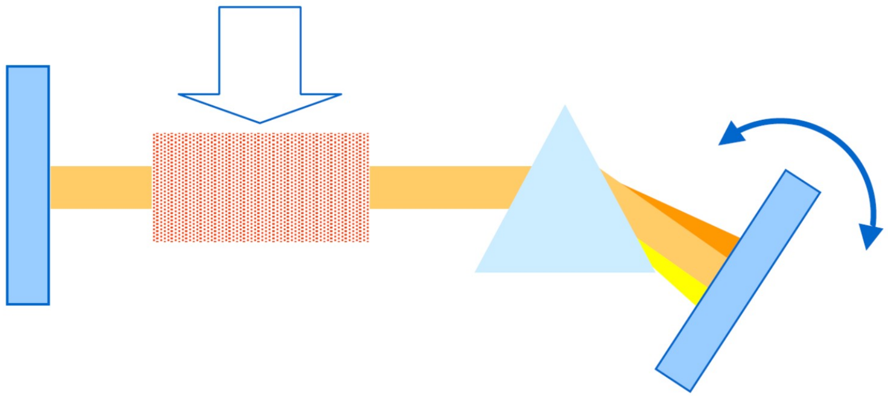
E.g. dye laser
Ti:sapphire

Their wavelength can be tuned by inserting
wavelength-selective elements within the laser cavity



Littrow mounting

- pulsed dye lasers
- external cavity diode lasers



- visible and near-IR

Transverse modes

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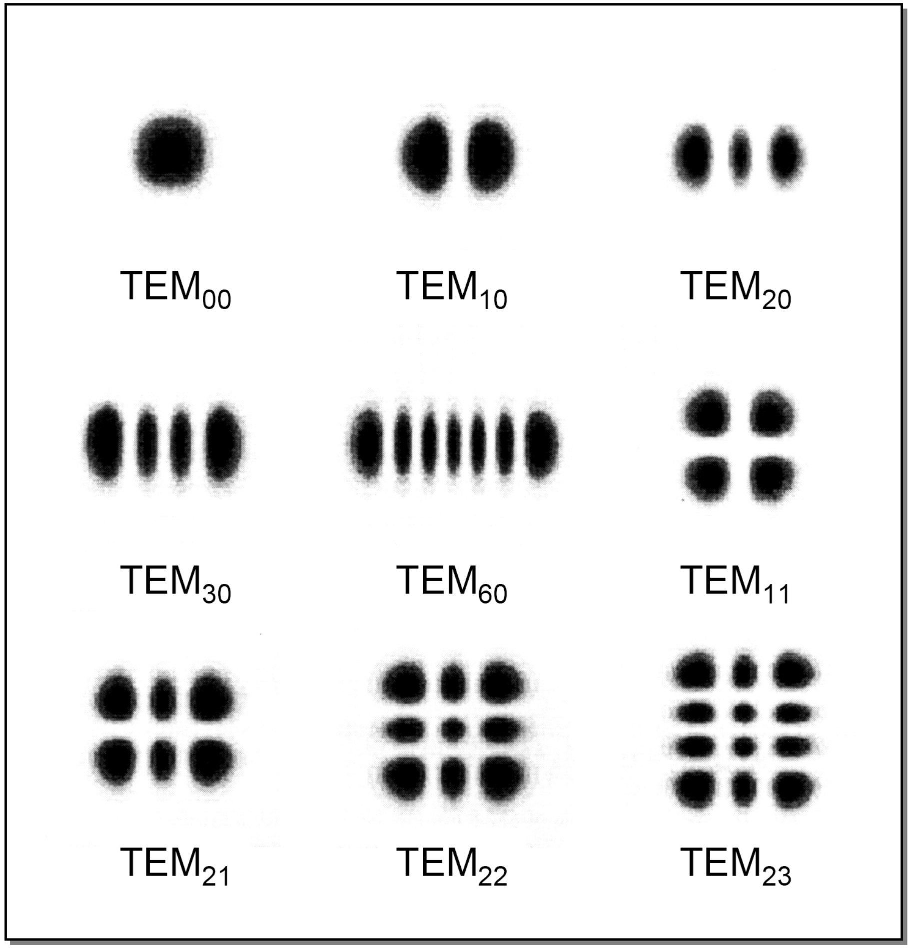

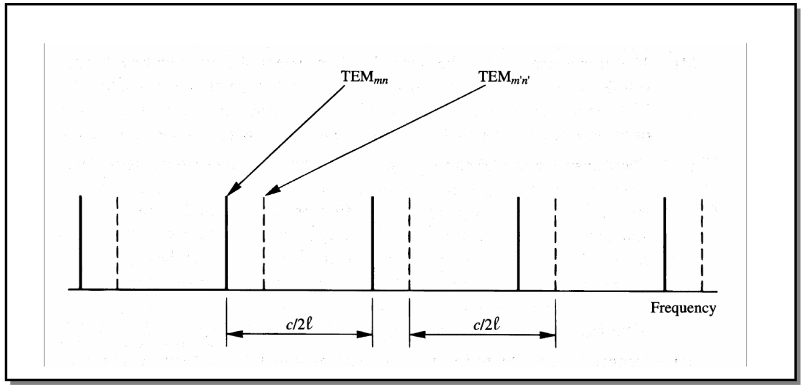

OBS. To each transverse mode there corresponds a set of **longitudinal modes** spaced by c/2*L*

Energy levels of laser

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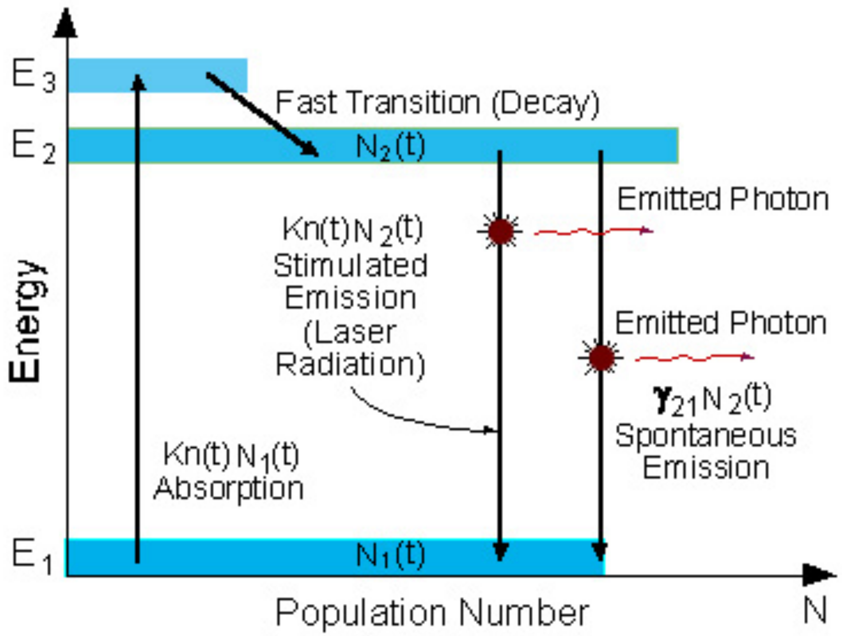
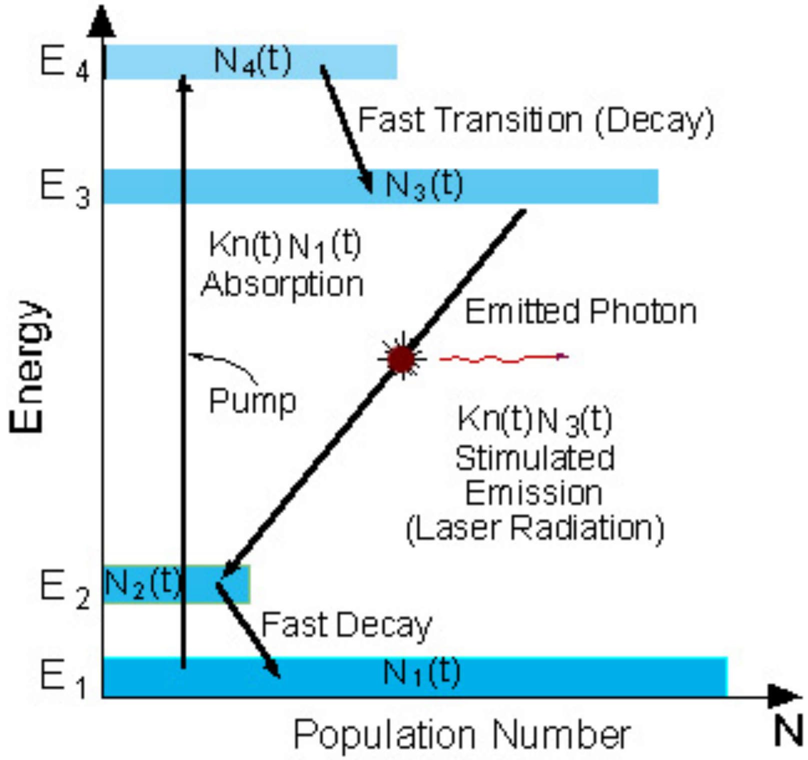
Three-level laser



Four-level laser



Types of laser

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- **Gas lasers** (helium-neon “HeNe”, Ar-ion, CO_2 lasers, etc.) have a gas lasing medium and they are usually continuous-wave (CW) laser which generates laser beam continuously. They are famous in generating stable high-power laser beam. Large laser cooling capacity is required to take away wasted heat because of their low energy conversion efficiency. They are gradually replaced by solid-state lasers.
- **Excimer lasers** (the name is derived from the terms *excited* and *dimers*) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range. When lased, the dimer produces light in the ultraviolet range. They are therefore popularly used in material processing and lithography.
- **Dye lasers** use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths. They have been greatly used in research laboratories because of their large wavelength tuning range. Because of the trouble in handling toxic chemical waste (dyes and solvents), they are gradually replaced by broad-band solid-state lasers and optical parametric oscillators.
- **Solid-state lasers** have lasing material distributed in a solid matrix (such as the ruby, neodymium:yttrium-aluminum garnet “Nd:YAG", Ti:sapphire lasers). They are almost the most reliable laser, requiring minimum maintenance and producing high power.
- **Semiconductor lasers**, sometimes called diode lasers, are not solid-state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, such as the writing source in some laser printers or CD players. Nowadays, they can produce large power and can be used to pump other lasers (such as solid-state lasers), making stable and compact high-power lasers possible.

Argon-ion laser

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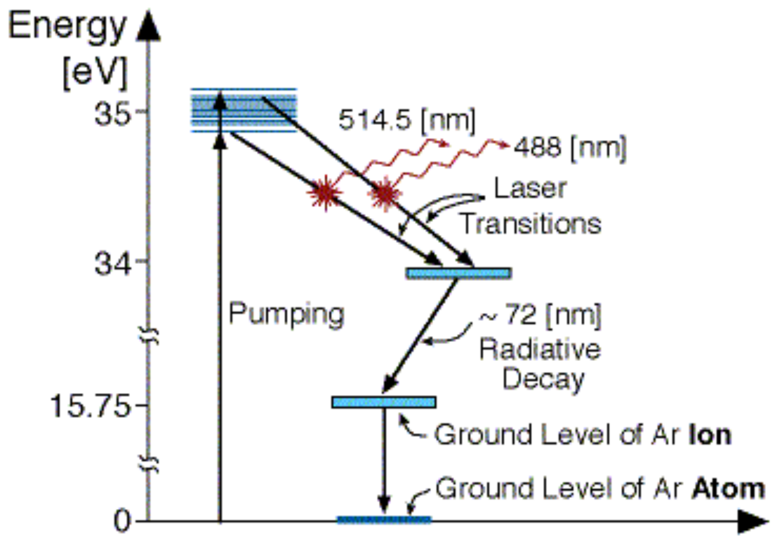
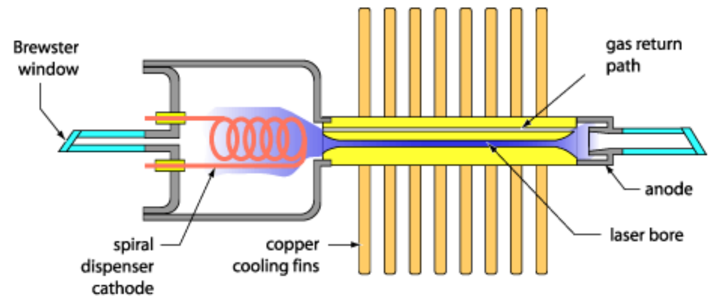
- Argon ion laser contains a tube filled with argon gas which transforms into plasma in an excited state.
- When considering the power output of the argon laser, it is important to state if the power output is at all the laser lines together, or at a specific wavelength.
- As seen in the energy diagram, the ground state of the laser at about 16 eV above the ground state of the neutral argon atom. This is a large amount of energy that must supplied to the laser, but is no used for creating laser radiation. This "wasted" energy is one of the reasons for the very low efficiency of the argon laser (0.1%).
- A high current density is required to maintain the argon plasma and thus create large amounts of heat which must be taken away from the laser. Argon ion lasers require air or water cooling.





Air-cooled Ar-ion laser structure

Excimer laser

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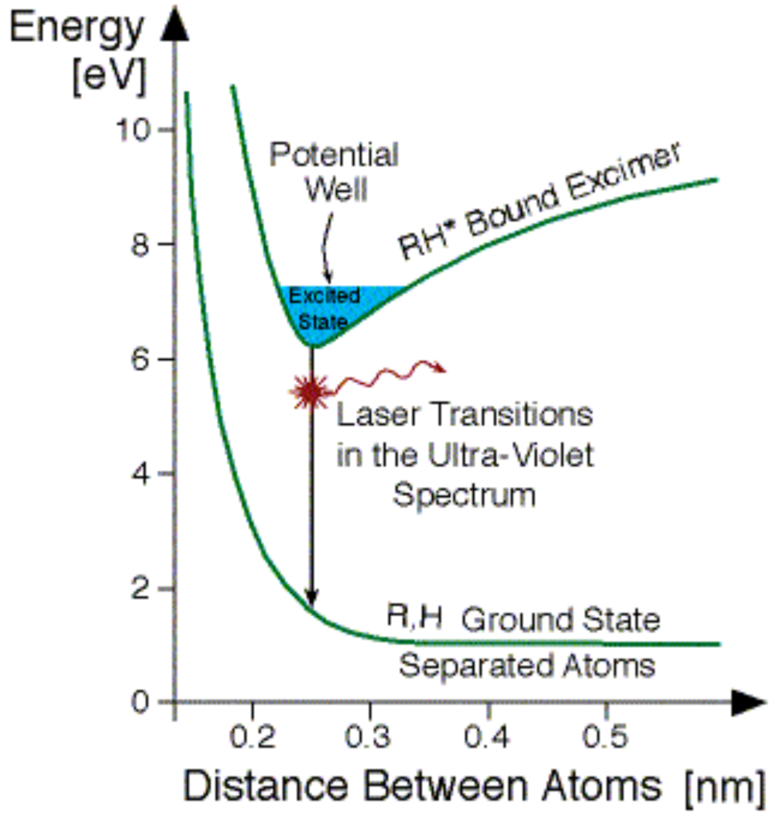
- An excimer is a molecule which has a bound state (existence) only in an excited state. The excited state exists for less than 10 ns.
- The condition of population inversion is achieved at the moment that there is an excited state, since the population of the lower laser level is always zero.
- Excitation of the excimer laser is done by passing strong electric pulses through the gas mixture. The excitation must be for a very short time and with a very high power, starting at about 100 kW/cm^3, and going to a few 10^6 W/cm^3.
- Care must be taken to choose the right materials inside the cavity, because of the high reactivity of the gases.
- Since the gases inside the excimer laser are very toxic, the laser must be sealed off after gas refill. The laser is used for a few million pulses, and then a gas refill is necessary.



R: noble atom; H: halogen atom

Semiconductor laser

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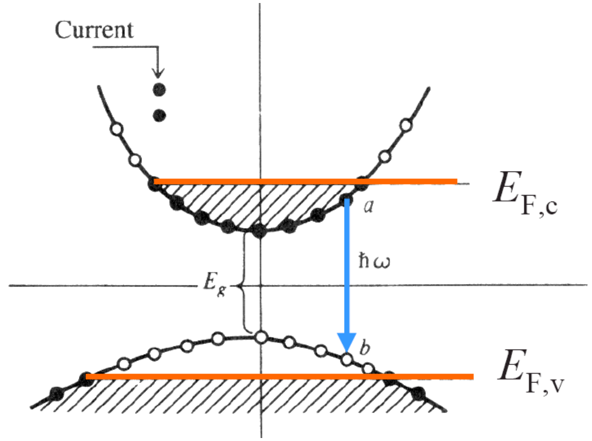
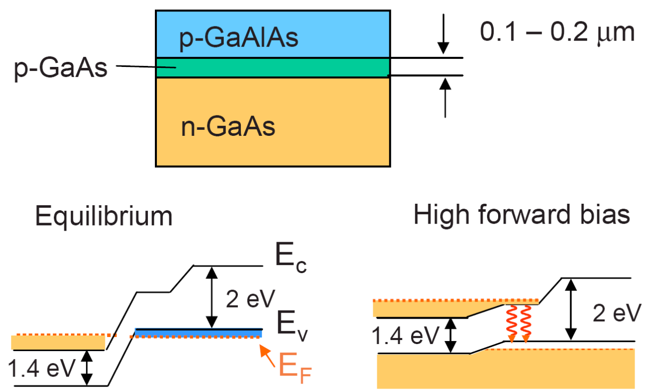
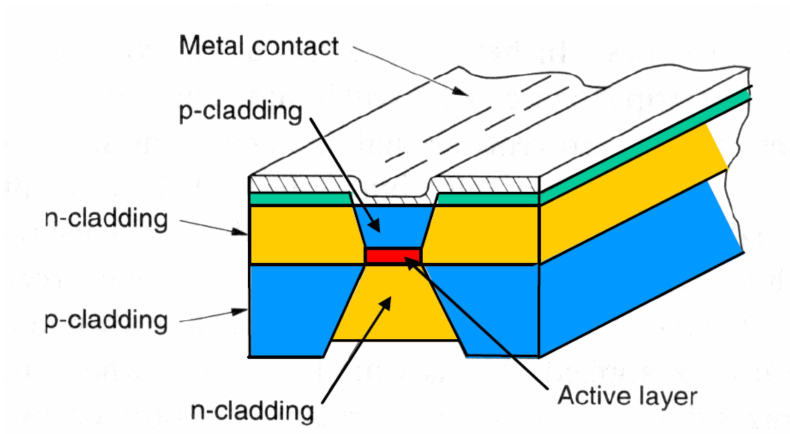
- Good efficiency (40-50%)
- Compact
- Low price
- Tunable wavelength
- Beam divergence
- Requires cooling

Energy diagram





Heterojunction laser



Index-guiding structure

Solid-state lasers

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- A **"neodymium:YAG" (Nd:YAG) laser**, a kind of solid-state laser, consists of a crystal of yttrium aluminum garnet (YAG) with a small amount of neodymium added as an impurity (0.1% to 1%). The Nd:YAG laser has a four-energy-level structure.
- The requirements for the host material are transparency to both the pumping and laser wavelengths and relatively good thermal conductivity. If the heat isn't removed fast enough from the interior of the laser rod, the host overheats and distorts the optical quality of the rod.
- A solid-state laser also consists of a pumping light source and a pump cavity. If the pump source is a flashlamp or tungsten arc lamp, the lamp may simply be placed next to the rod, or lamps may be placed at the foci of elliptical mirrors, with the laser rods at the other focus.
- The resonator of solid-state lasers has to compensate for thermal lensing caused by the uneven heating of the laser rod and usually uses a curved mirror or a combination of mirrors and lenses to refocus the beam, producing narrow divergence.
- In Q-switching, an electro-optic or acousto-optic switch acts to block the transmission inside the cavity. Because photons inside cannot build up the laser beam energy, a population inversion much larger than needed for lasing can be built up. When the cavity is suddenly changed to a transmissive one, an intense laser pulse rapidly drains the higher energy level in a time much shorter than a normal pulse.

Major solid-state lasers

Major solid-state lasers and applications

LASER ION	HOST MATERIALS	MAIN LASER λ	PUMPED BY	APPLICATIONS
Nd^{3+}	YAG YLF YVO_4 Glass	1.064 μm 1.055, 1.047 1.0 1.055	Diode arrays near 808 nm or lamps	Industrial, scientific, medical, and military. Glass host used for very large energies or enormous peak power for laser fusion.
Yb^{3+}	YAG Glass fiber	1.03 μm 1.02 to 1.06	Diode arrays at 940 nm	Under development for industrial and military.
Er^{3+}	Glass Glass fiber	1.54 μm	Diodes pumping Yb near 960 nm with energy transfer. Lamp pumping with energy transfer.	Military eye-safe rangefinders Fiber communications
Er^{3+}	YAG	2.94 μm	Lamps or diodes	Medical and dental; λ near 3 μm has large absorption coefficient in tissue.
Ho^{3+}	YAG, YLF	Several lines near 2 μm	Diodes @ 794 nm by energy transfer from Tm^{3+}	Surgical cutting at ~100 W; strong absorption in tissue and bone.
Tm^{3+}	YAG, YLF	Several lines near 2 μm	Diodes @ 794 nm	Significant potential market in coherent wind speed measurements from airplanes.
Cr^{3+}	Al_2O_3 (ruby) Alexandrite (tunable)	0.694 μm	Flash lamps (Nonstandard diodes)	Ruby: military designators, pulsed holography, scientific
Ti^{3+}	Al_2O_3 (Ti: sapphire)	650 nm to 950 nm (tunable)	CW Ar ion, Nd + SHG	Scientific, ultrafast

Flash lamp-pumped Nd:YAG laser

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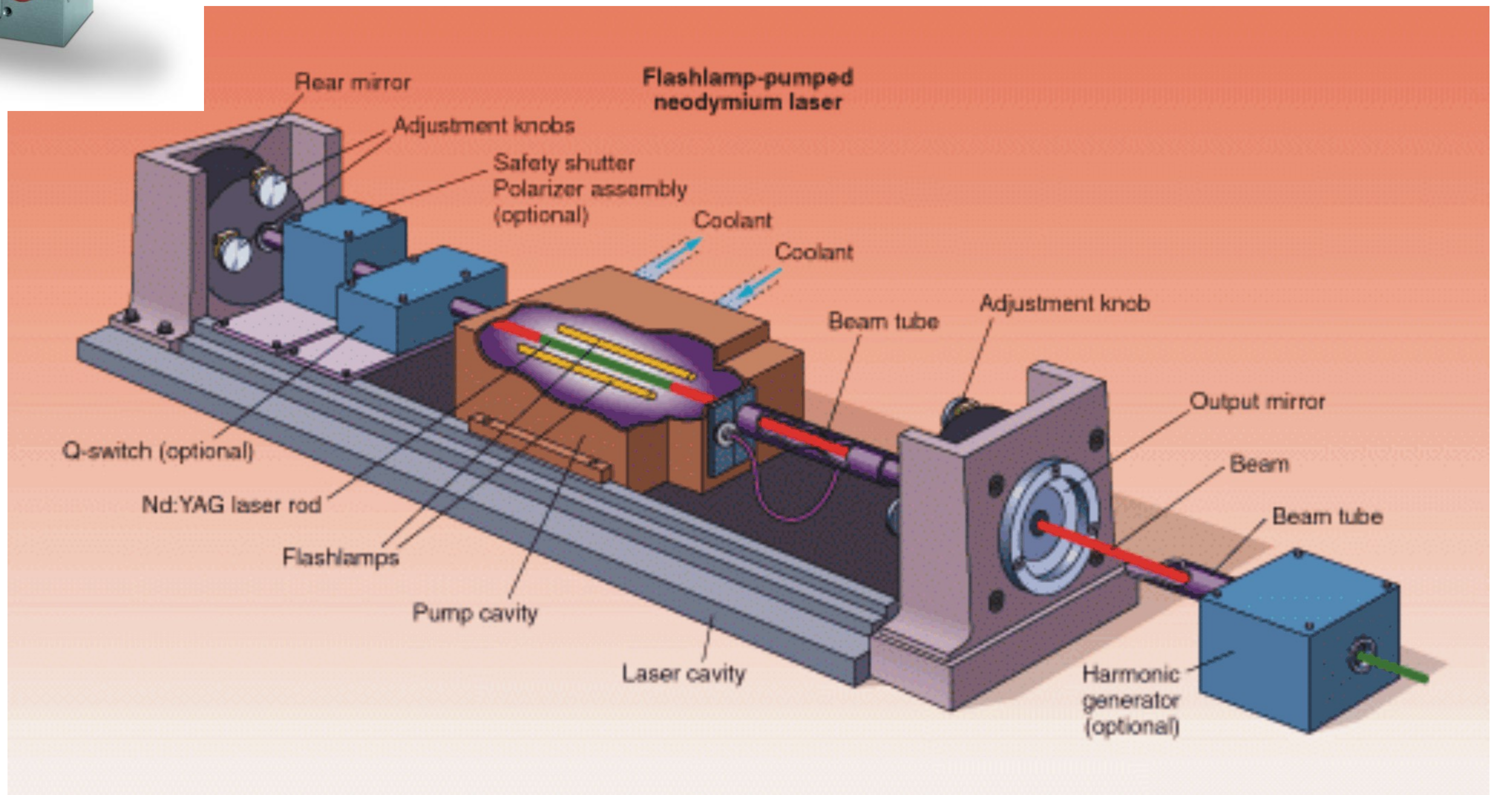

Diode-pumped Nd:YVO_4 laser

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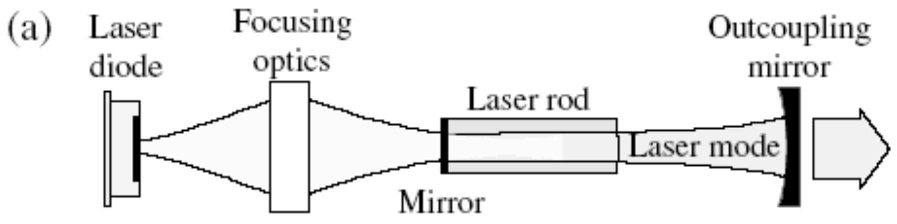
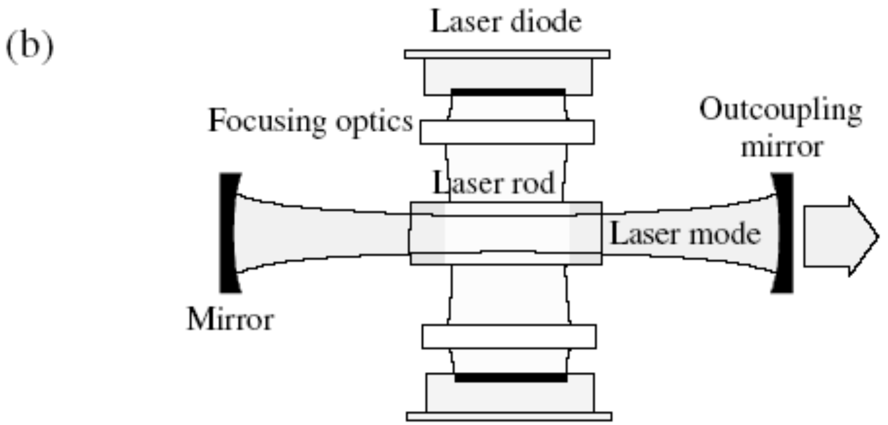
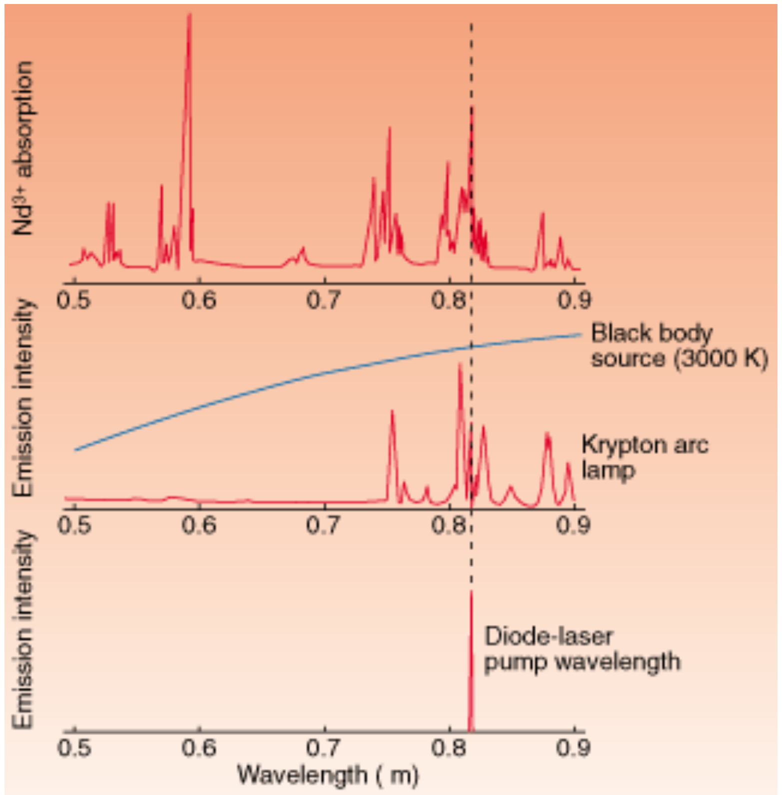
Longitudinal pumping



Transverse pumping





Narrow-linewidth Pulsed dye laser

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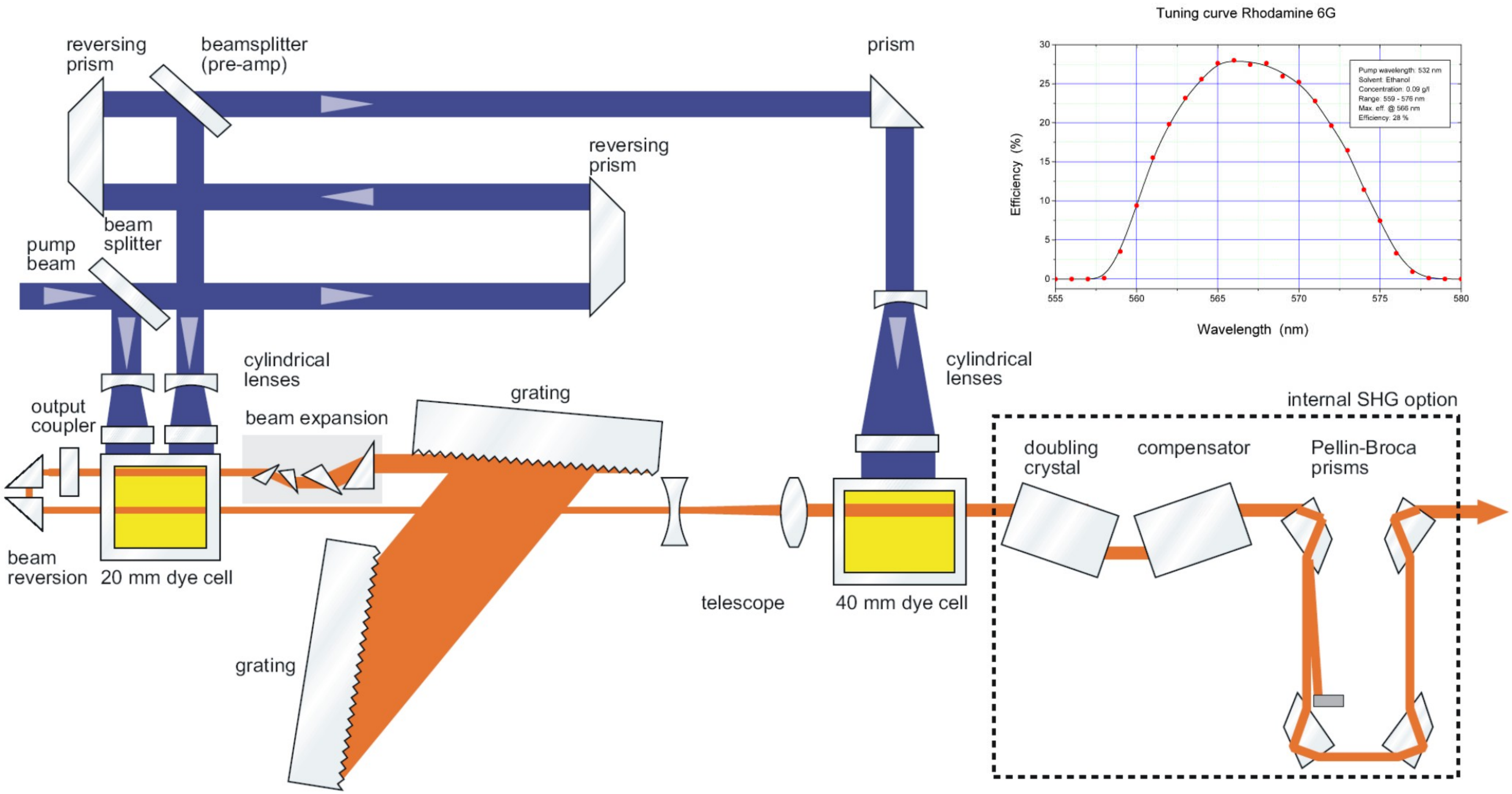

Evolution of ultrashort laser pulses

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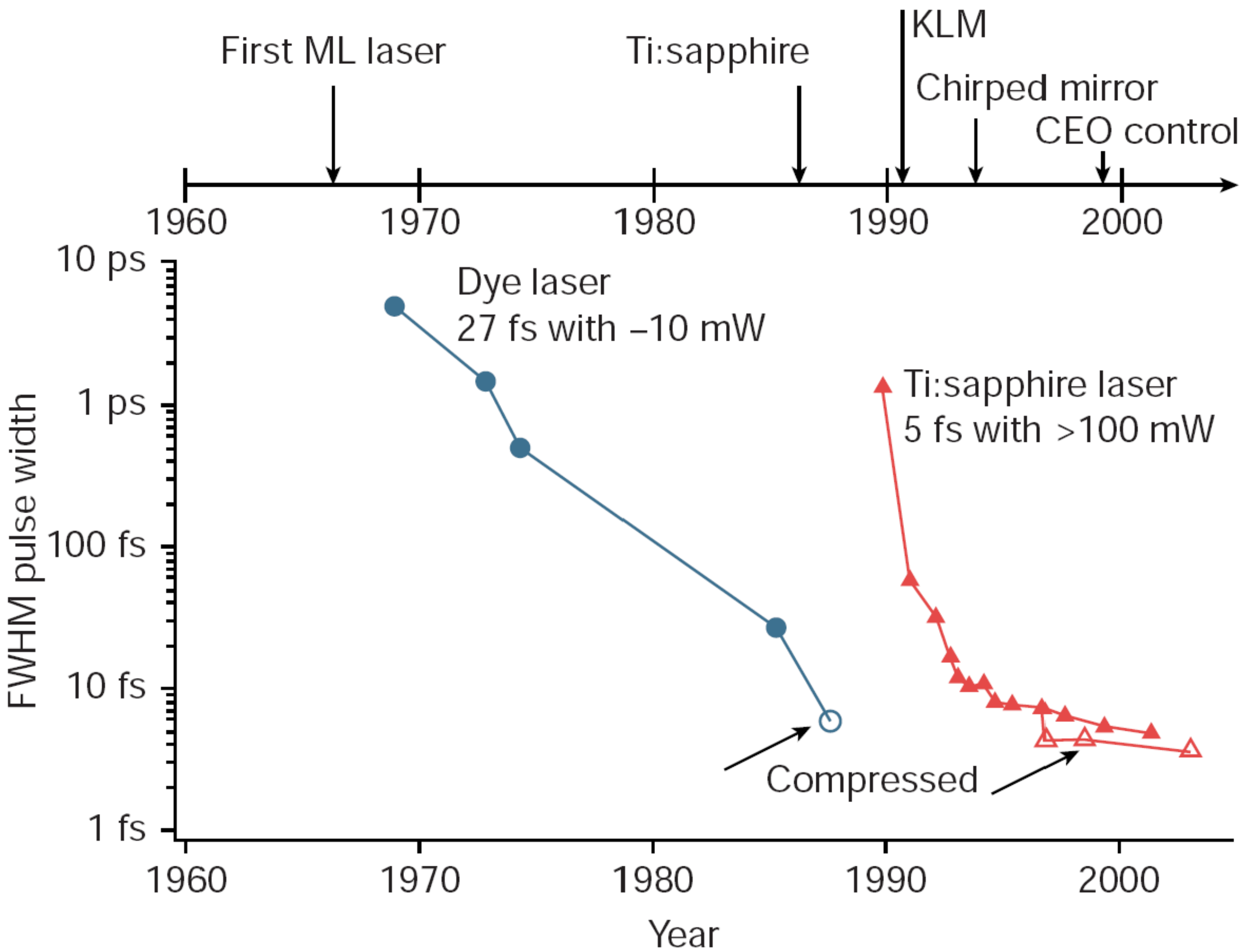

U. Keller, Nature 424, 831 (2003).

Mode locking

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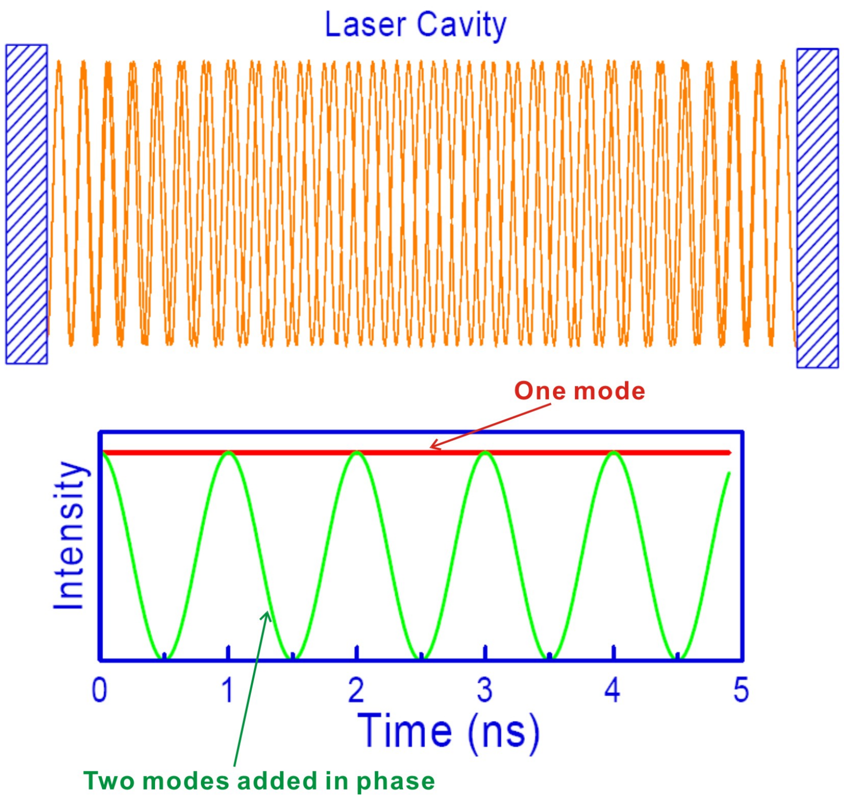

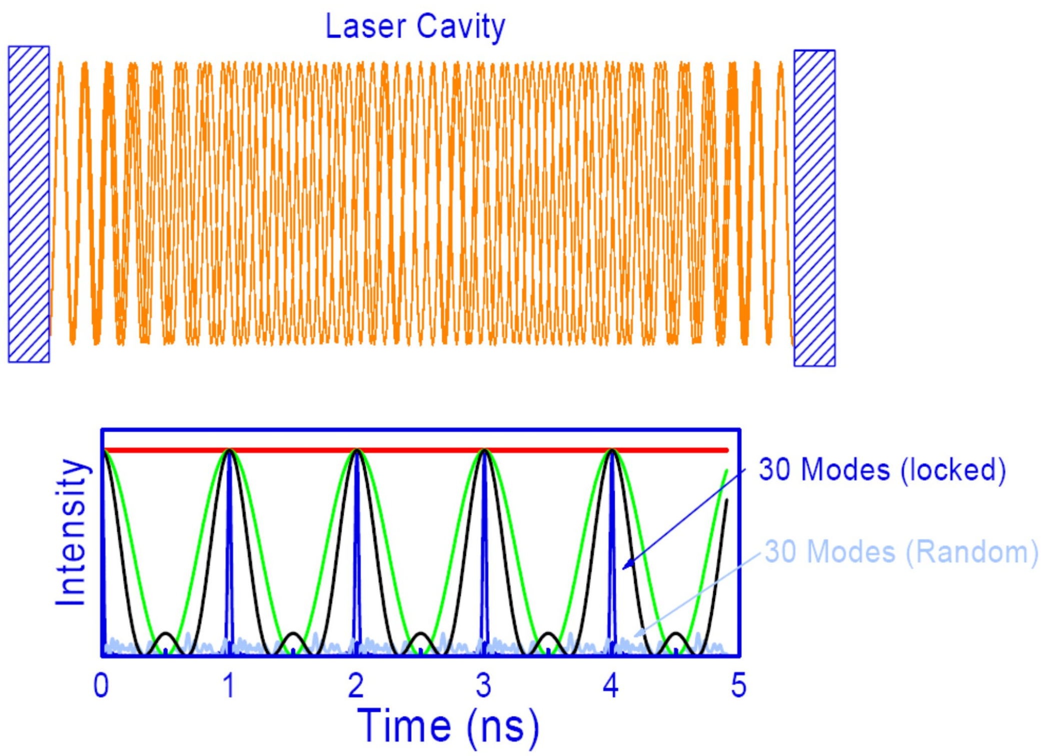

Generation of mode-locked pulses

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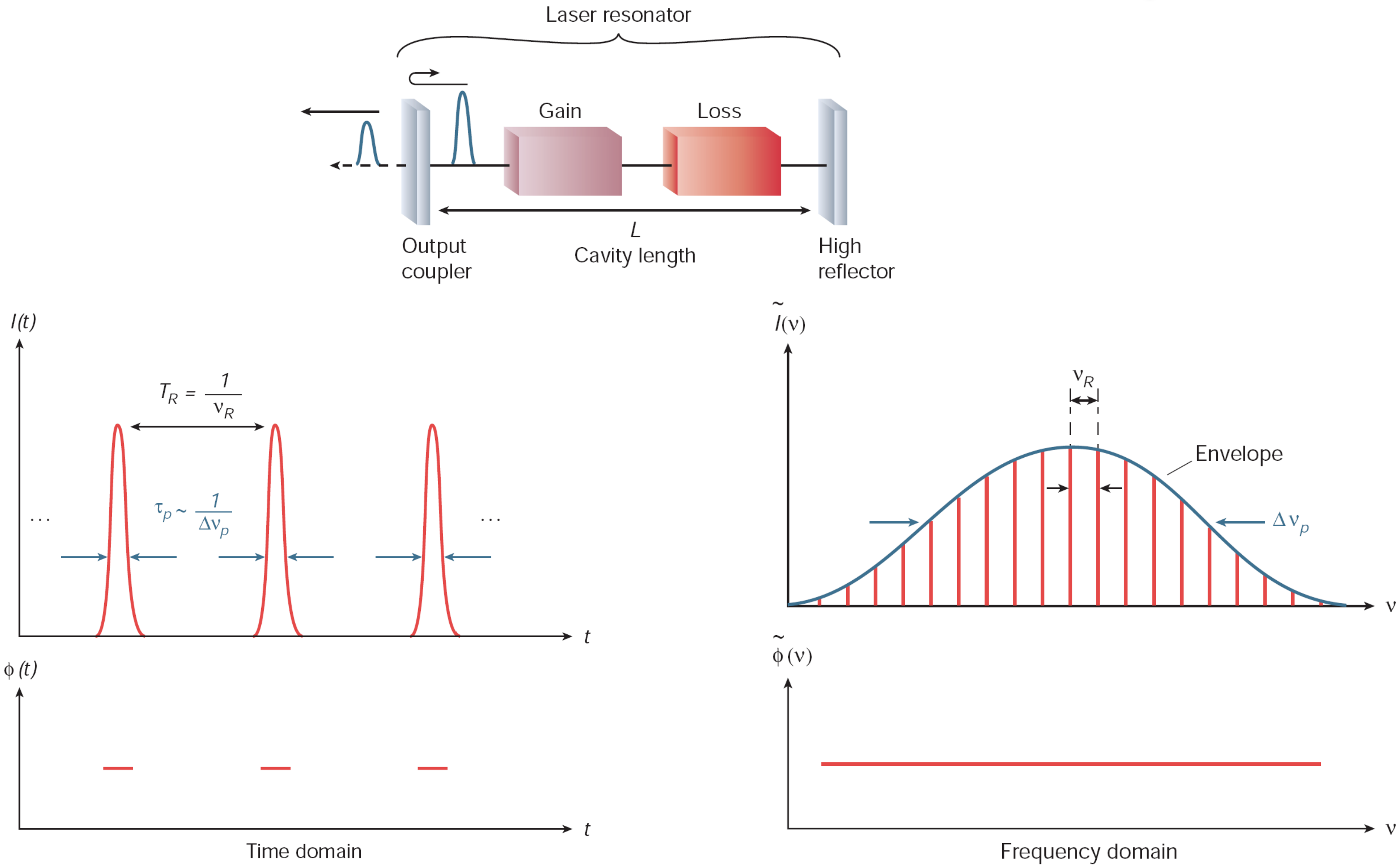

U. Keller, Nature 424, 831 (2003).

Mode-locked Ti:sapphire laser

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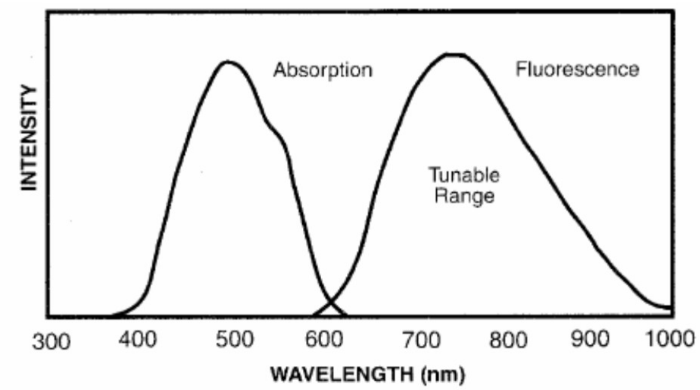
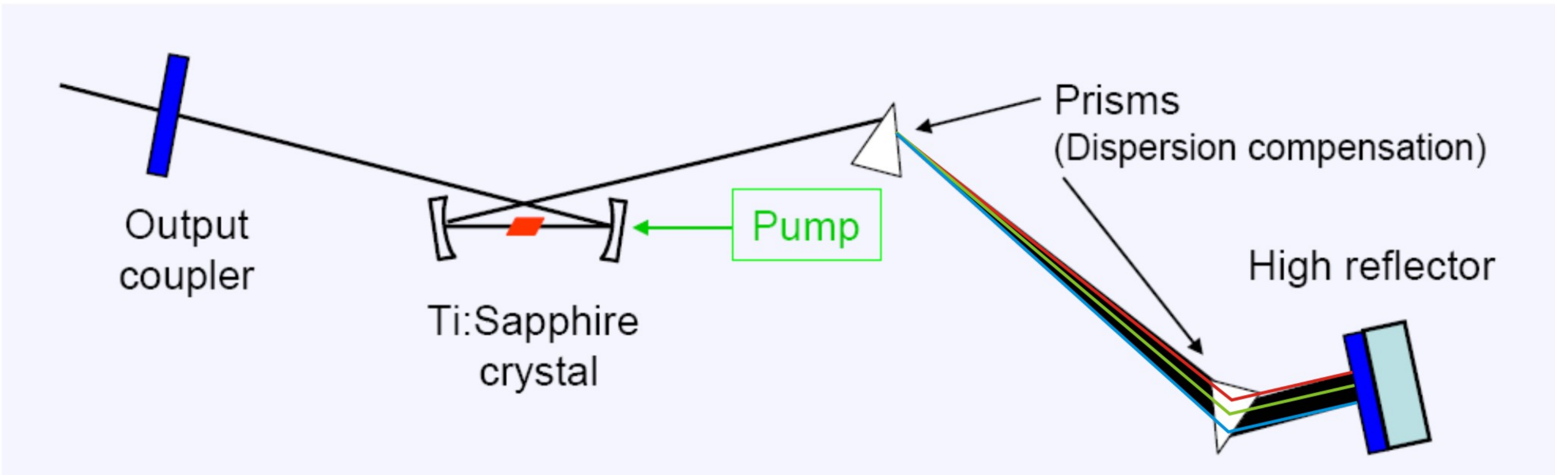
- Ti:sapphire has large bandwidth
- Supports shortest pulses
- Simple (amazingly)





Ultrahigh peak power density

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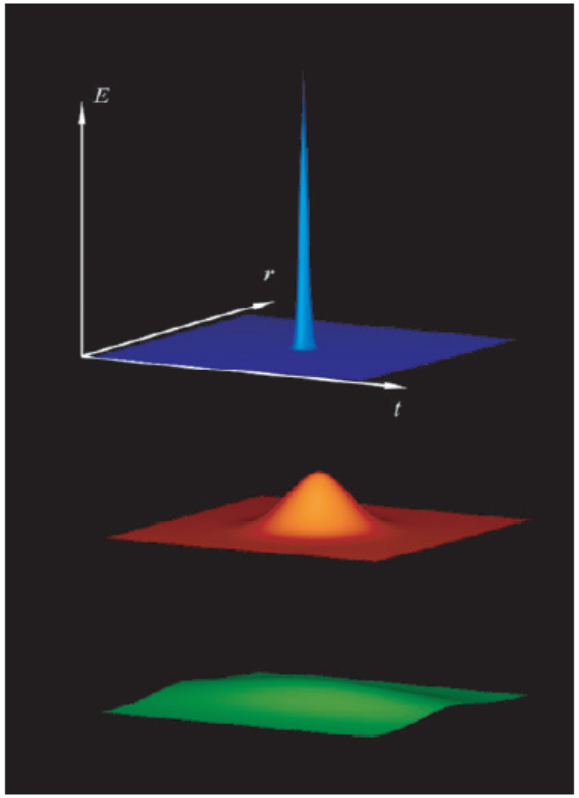

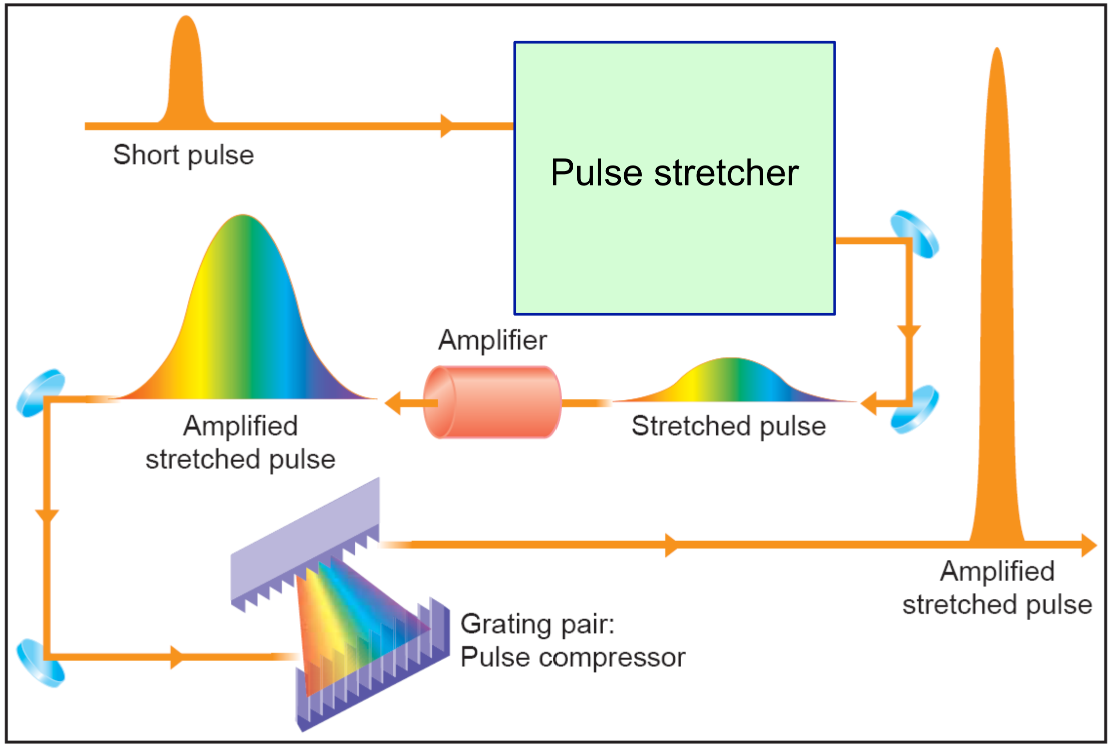

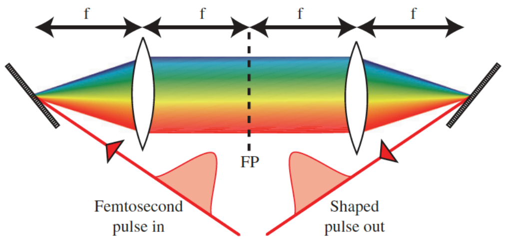

Pulse stretcher

Considerations in laser cooling

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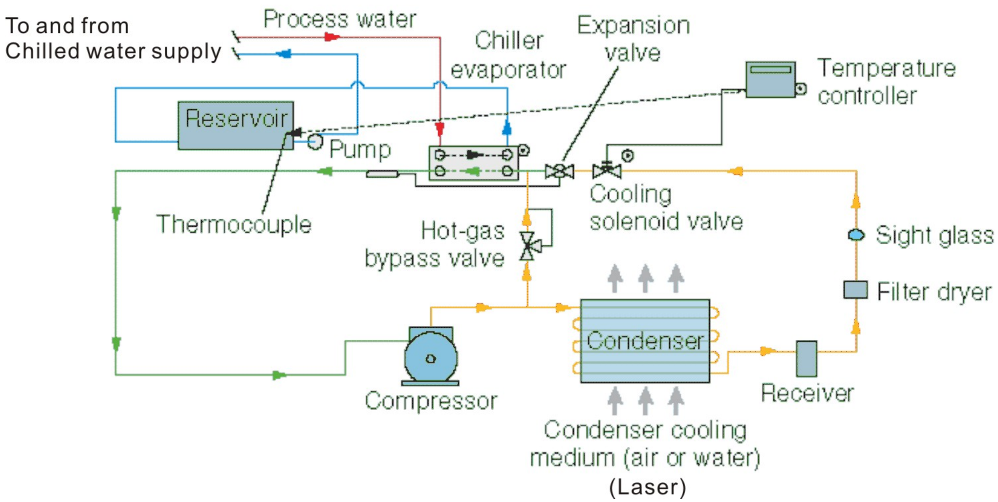
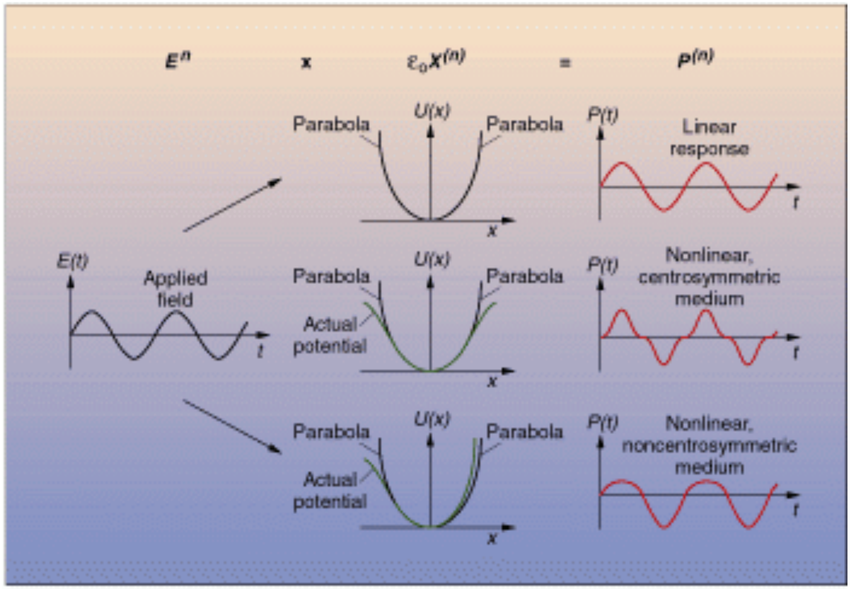
- **Know the heat load of the laser**
- **Air-cooled vs. water-cooled**
- **Open-loop vs. closed-loop**
- **Unrefrigerated vs. chiller:**
  - Unrefrigerated ($T_{set} > T_{amb}$)
  - Chiller ($T_{set} < T_{amb}$, $\Delta T = 0.1$°C)
- **Tap or deionized water**
  - Corrosion
- **Flow speed and pressure**
  - Interlock system
- **Construction materials**
  - Pipes and reservoir tank
- **Control system**
  - Temperature stability
  - Warning



Nonlinear optical response

- When light passes through dielectric matter such as glass, the dipole model describes the interaction between an oscillating electric field (the light wave) and a collection of harmonically driven dipoles (the atoms). At conventional irradiance levels (several W/m^2), the atomic dipoles respond linearly to the driving force of the light wave. But at very high levels of irradiance (several MW/m^2), the dipoles no longer respond linearly and therefore begin to oscillate anharmonically.
- If two monochromatic light waves of differing frequencies pass together through the same non-centrosymmetric medium, the resulting complex polarization wave induced in the material contains components at the two fundamental frequencies (n_1, n_2), the second harmonics of both fundamentals ($2n_1$, $2n_2$), the sum and difference frequencies of the two fundamentals ($n_1 \pm n_2$), and a dc component ($n = 0$). This polarization wave contains all the elements of linear and second-order nonlinear optical effects.

$$P \propto \ldots + \chi^{(2)} E_j E_k + \chi^{(3)} E_j E_k E_l + \ldots$$



Electro-optic modulation

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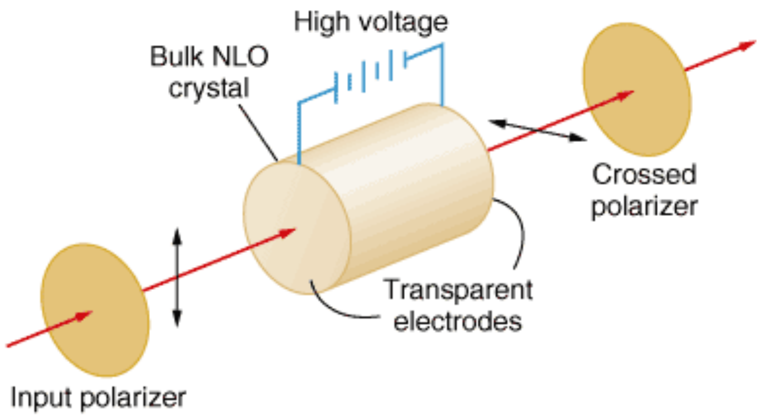
- Electro-optic modulators control the polarization of light passing through a crystal subjected to an electrical driving signal. In terms of nonlinear optics, one of the frequency (say n_1) is equal to zero.
- The most commonly used crystals for e-o modulators constrain the vibration of propagating light waves in two mutually perpendicular planes of polarization determined by the symmetry axes of the crystal (o- and e-ray). Through the crystals of this class, only one direction will the wave velocity be the same for both planes of polarization. That direction is the optical axis.
- When an electric field is applied to a uniaxial crystal parallel to its optic axis, the indices is no longer equal. The vibrations then do not have equal velocity, and a phase difference or retardation now exits. Thus, electro-optic modulator works as an electrically controlled wave plate.



Second-harmonic generation (SHG)

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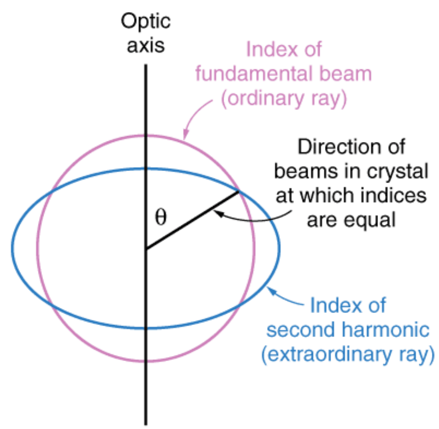
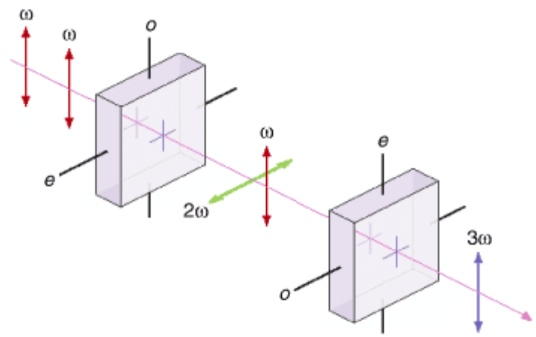
- In SHG, the nonlinear polarization wave moves through the material with a phase velocity that matches the primary refracted wave. This is because the refracted wave induces the material polarization. But the SH light wave travels more slowly through the medium due to dispersion. Consequently, the polarization wave and its ensuing SH light wave pass in and out of phase with each other as they propagate through the material. Because they cannot add constructively, the energy exchange between them is limited.
- To maximize the energy transfer, the phase velocities of the two waves must match, enabling a cumulative buildup of the second-harmonic wave in the forward direction. And one of the most convenient ways to achieve this is to use birefringent crystals whose refractive indices depend on the direction and polarization of the propagating light. If a polarized light wave passes through a birefringent crystal at just the right angle, the phase velocities of the induced polarization wave and second-harmonic wave can be made equal. In crystals such as lithium niobate, angle phase matching can convert the fundamental frequency to its second harmonic with great efficiency.





Laser wavelength extension by SHG

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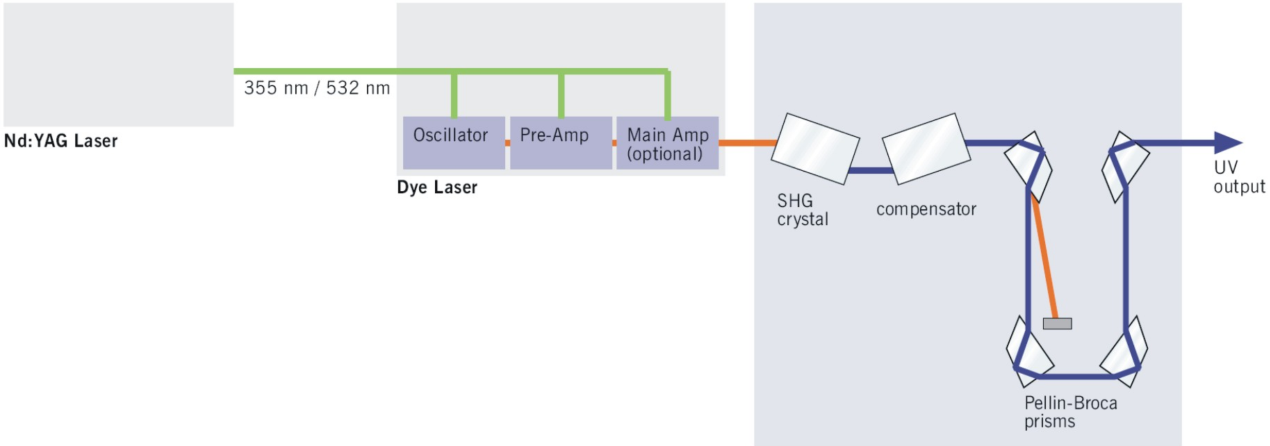

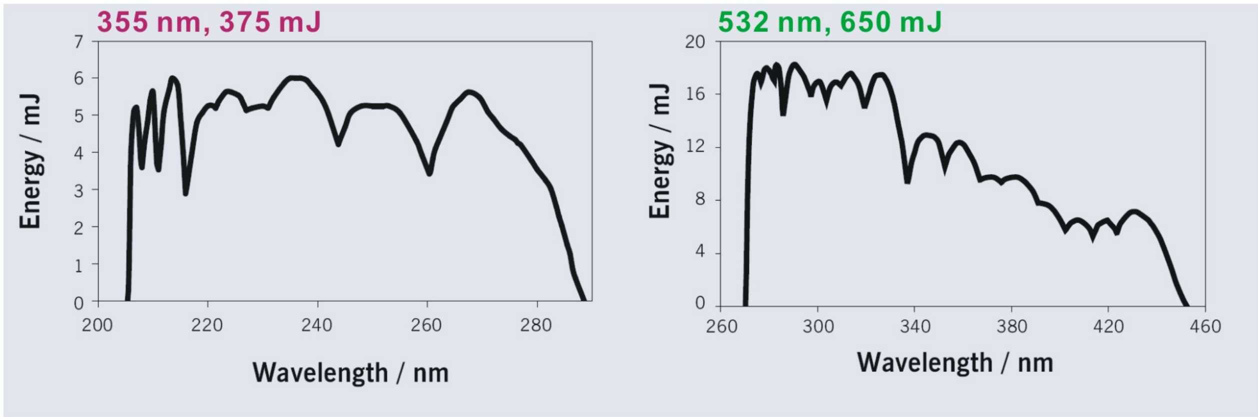

Optical parametric oscillators (OPO)

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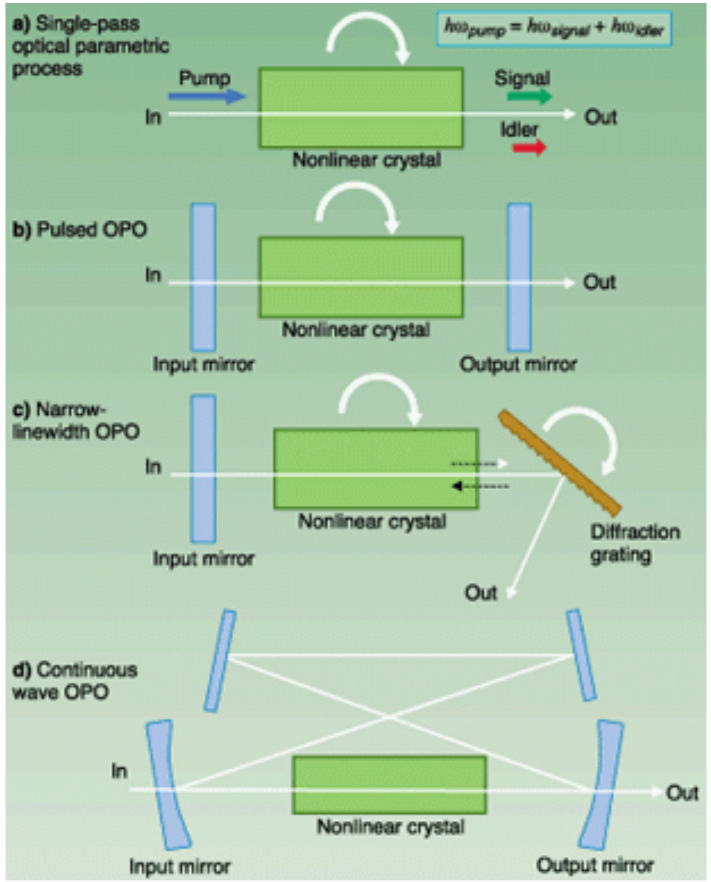
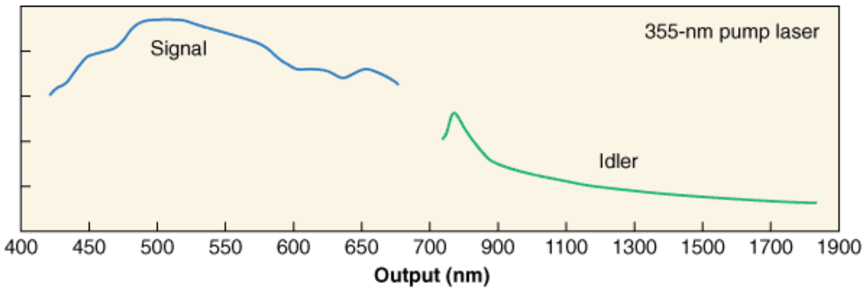
- An OPO converts monochromatic laser emission (pump) into a tunable output via a three-wave mixing process. The heart of an OPO is a nonlinear-optical (NLO) crystal in which the pump photon decays into two less-energetic photons (signal and idler) so that the sum of their energies is equal to that of the pump photon. An important further constraint is that the sum of the signal and idler wave-vectors must equal that of the pump ("phase-matching" condition). Rotating the crystal (in angle phase matching) changes the ratio between the signal and idler photon energies, and thus tunes the frequency of the output.





Laser safety issues in human eyes

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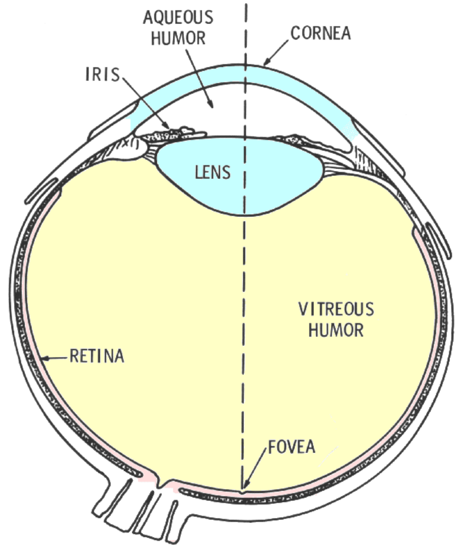
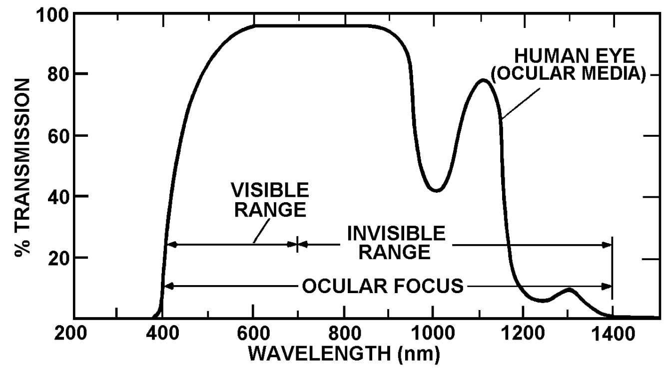
- **Human eye structure:** The *cornea* is the main focusing element, and the *lens* performs fine focusing duties. The space between the cornea and lens is filled with a watery liquid known as the *aqueous humor*, and the interior of the eyeball is filled with the jelly-like *vitreous humor*. The *retina* is the screen upon which the cornea and lens project an image of the outside world. The *fovea* is the seat of sharp vision. The retina is connected to the brain by the *optic nerve*. Signals generated in the retina are transmitted by the optic nerve to the brain, which interprets these signals as vision. **The cornea, aqueous humor, lens, and vitreous humor are called the *ocular media*. They are the stuff through which light must pass to reach the retina.**
- **Transparency of the ocular media** extends into the infrared (IR)-all the way out to 1400 nm, in varying degree. The retina normally does not respond to wavelengths much longer than about 760 nm, so this light is invisible, even though it reaches the retina. This creates special hazards. **This wavelength region, 400 -1400 nm, is called the *retinal hazard region*.**
- For a 0.25 *m*J laser pulse, it will be focused by the *lens* to reach **the damage threshold of retina** (10 mJ/cm^2).





Safety rules in laser lab

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- **Accidental reflections:** **Watches** must be taken off before any alignment. The same holds for **belt buckles**, **jewelry**, etc. that could deflect a beam to eye level.
- **Safety goggles:** Goggles must be worn whenever covers are removed from any of the commercial laser systems. For each commercial laser system **two pairs of matching safety goggles** must therefore be available.
- **Laser safety items :** For each commercial laser system, a laser warning sign should be attached with a description of it power and wavelength. A **warning sign** should be attached on each entrance door to the lab and an illuminated warning sign should be installed at the main entrance. **Safety curtain** or barrier should be installed around the laser danger area (such as optical table, chamber, etc.)
- **Stray beams:** Whoever moves or places an optical component on an optical table is responsible for identifying and terminating each and every stray beam coming from that component. **Unsecured pieces of cardboard are not suitable beam terminators.**
- **Vertical beams:** Any place where a laser beam travels out of the horizontal plane must clearly be marked with **yellow tape** on the optical table and a solid stray beam shield must be securely mounted above this area to prevent accidental exposure to the laser beam.
- **Chambers and cells:** Before looking into an optical cell or chamber all laser beams traveling into it must be blocked.
- **Leaving lab:** **When operating, lasers may not be left unattended**, unless all doors to the lab are locked. Even if only momentarily leaving a room, lock all doors.
- **Visitor safety:** Before admitting any visitor into the laser laboratory the admission criteria must be checked (over 150 cm; no covers off; no stray beams above table height) and the visitor must be given the admission information (potential eye-injury/vision-loss hazard; no bending or sitting down; no bending over any optical table). **Unaccompanied visitors are not allowed.**

Laser safety products

Warning sign

Safety eyewear

Safety curtain & barrier

Illuminated warning sign

Beam dump

Guidelines for the first-time laser user

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- Read the manual carefully
  - Safety concern
  - Basic principle and layout
  - Operating procedure
  - Maintenance and trouble-shooting issues
- Talk to the laser manager
  - How the laser is installed (electricity, cooling water, etc.)
  - Laser log book
  - Safety issues
- Know what you can do and what you can not do
- Operate the laser under a guidance of the laser manager

Radiometry and photometry

Dr. Juen-Kai Wang, CCMS & IAMS

- Radiometry is the measurement of optical radiation at wavelengths between 10 m and 1 mm. Photometry is the measurement of light that is detectable by the human eye, and is thus restricted to wavelengths from about 360 to 830 nm. Photometry has an added layer of complexity—measurements are factored by the spectral dependence of human vision. Also, as a practical matter, displays and sources of illumination often have a spatial dependence not found in most non-diode laser sources.
- Early measurements of light power compared what the eye perceived to the artificial sources then available. Modern units in the science of photometry are derived from this "standard candle" and are used in the characterization of displays and illumination. The candela is the fundamental SI unit of optical measurement, equivalent in kind to the kilogram and the second.
- Most optoelectronic measurements use radiometric units of power and energy familiar from electrical measurements—watts, joules, and so forth. The lumen is the photometric analog of the watt. There are 683 lumens per watt at 555 nm, at which the spectral responsive of the human eye is a maximum (the luminosity curve is set to unity). At other wavelengths, the conversion is scaled to the standard luminosity curve.
- The candela can be thought of as the product of lumens and solid angle. There exists a bewildering variety of photometric and radiometric quantities and associated units (Talbots, nits, and blondels, for example). Modern instruments are capable of displaying whatever units are best suited to the application, reducing the burden on the user.

Photodetector response

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- Quantum efficiency (η) is a fundamental measure of photodetector response, defined as the probability that an incident photon will generate a tangible charge carrier. Even the most sensitive detectors have quantum efficiencies of less than one.
- Responsivity (R) represents voltage or current output produced by a given optical power irradiating the detector. Called spectral responsivity when measured as a function of wavelength and blackbody responsivity when integrated over all wavelengths. (units: V/W or A/W)
- Noise equivalent power (NEP) is the optical power needed to generate an S/N = 1. NEP is related to responsivity by the formula Nrms/R, where Nrms is the root-mean-square noise voltage (or current). NEP defines the minimum detectable raw signal. (units: W)
- Detectivity (D) is the inverse of NEP (1/NEP). Contrary to NEP, detectivity increases with increasing detector sensitivity. (units: 1/W)
- Specific detectivity (D*): Because the NEP of most detectors varies in proportion to the square root of both the surface area and the electronic bandwidth, these two parameters must be factored out before detectors with unequal areas can be equitably compared at different frequency bands. Thus, $D^* = \sqrt{(A \cdot \Delta f)}/NEP$, where A is the area and Δf is the bandwidth. (units: $cm \cdot \sqrt{Hz}/W$)
- Frequency response: When the incident optical power is modulated or "chopped" on and off at increasing rates, frequency response specifies the modulation frequency at which the detector`s response drops to one half of its low frequency level. It also reflects the response time of the detector.

Photodetection noise-I

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- The ultimate measure of worth for a detector is how well it isolates signal from noise. Detector response always includes a mixture of signal and noise, and the ratio between the two depends on the detector`s design and its environment. The general goal of detector design is to maximize this signal-to-noise ratio (S/N).
- Photon noise originates from the random arrival of photons at the detector surface. Because of this randomness, the number of photons collected within a given time interval varies around some statistical average. Coherent laser light approximates a Poisson distribution, while incoherent blackbody radiation follows a broader Bose-Einstein distribution.
- Background noise represents light irradiating the detector from sources other than the one of interest.
- Dark current is a randomly fluctuating current that flows through a detector in the absence of light. It usually arises from the thermal excitations of charge carriers within the detector.
- Johnson (Nyquist) noise is fluctuating voltage or current caused by the random thermal motions of charge carriers within a resistive medium.

Photodetection noise-II

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- Shot (Shottky) noise presents whenever current flows through a detector or circuit. It originates from the random arrival of charge carriers at any given point within the device.
- Generation-recombination noise is caused by random variations in the generation and recombination rates of free charge carriers within a photo detector.
- 1/f (flicker) noise is thought to originate from metastable electron traps and crystal dislocations within the photodetector and at ohmic contact sites. 1/f noise decreases with increasing frequency.
- Gain noise is caused by random fluctuations in the internal gain of photodetectors.
- Temperature noise is strictly a thermal detector noise resulting from temperature variations caused by energy sources other than the signal source.

Detector comparison

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Basic properties of detector families

DETECTOR TYPE	PEAK SENSITIVITY		SPECTRAL LINEARITY	RESPONSE TIME
Eye	Equivalent to PMT		Peaks near 555 nm	50 ms
Thermopile	55	V/W	Flat	1 s
Pyroelectric	2400	V/W	Flat	1 μs
PMT	10^5	A/W	Varies by type[1]	10 ns
Solar cell[2]	0.3	A/W	Peaks near 750 nm	200 μs
Photodiode[2]	0.3	A/W	Peaks near 750 nm	1 ns
Avalanche[2]	100	A/W	Peaks near 750 nm	1 ns

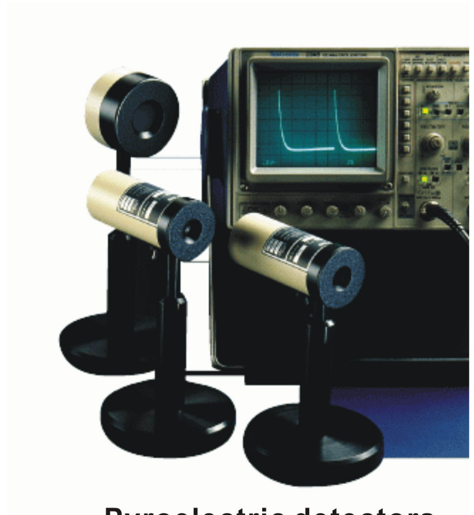
Adapted from Elements of Modern Optical Design by Donald O'Shea, John Wiley & Sons.

[1] Cathode material is selected for spectral characteristics.
[2] Refers to silicon-based detectors.

Power and energy detectors

- A thermopile is a collection of thermocouples connected to each other in series in order to achieve better temperature sensitivity.
- The bolometer takes advantage of temperature-dependent resistance changes that occur when various materials are exposed to light.
- The response time of the two thermal detectors above is slow (< 3 sec). They are therefore suitable for measuring average power.
- The pyroelectric detector employs a ferroelectric absorber element for radiant energy sensing. Ferroelectric materials possess a permanent internal dipole moment. As temperature rises, however, lattice vibrations reduce the material polarization of a ferroelectric. The induced surface charge variation can be measured with suitable electronics.
- The response time of the pyroelectric detector is about 50 μs. It is therefore suitable for measuring pulse energy of low repetition-rate laser (< 2 kHz).

Thermopile detectors



Pyroelectric detectors

Semiconductor photodetectors

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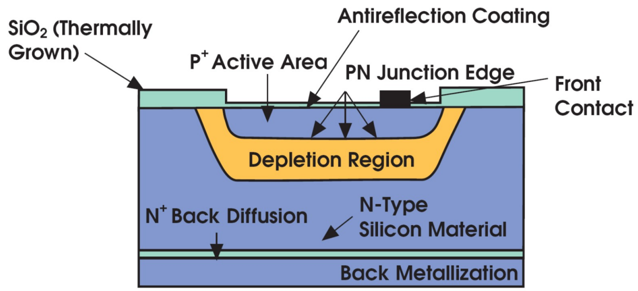
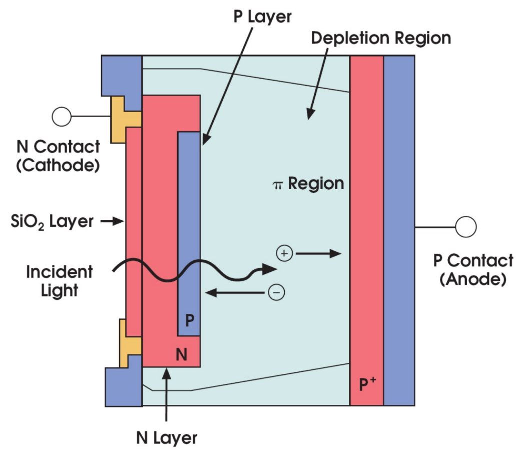
- A **semiconductor PIN photodiode** is a p-n junction where an area of neutral charge (the depletion region) sits in between. When light enters the device electrons and holes are excited into the conduction band if the energy of the light is greater than the bandgap energy. In the **photovoltaic mode**, electron hole pairs generated in the depletion region drift to their respective electrodes which produces a positive charge buildup which is directly proportional to the amount of light falling on the detector. In the **photoconductive mode**, a reverse bias voltage is applied, increasing the electrical strength and the depth of the depletion region. The advantages of such an operation are higher speed, lower capacitance, and better linearity.
- The **avalanche photodiode (APD)** is a specialized PIN photodiode designed to operate with high reverse-bias voltages. Large reverse voltages generate high electric fields at the p-n junction. Some of the electron hole pairs passing through or generated in this field gain sufficient energy (greater than the bandgap energy) to create additional electron hole pairs in a process called **impact ionization**. If these new pairs acquire enough energy, they also create electron hole pairs. This mechanism, known as **avalanche multiplication**, is the way APDs produce internal gain, which is an important attribute when the detector is combined with an amplifier.



P-I-N photodiode



Avanlanche photodiode

Photomultiplier tube (PMT)

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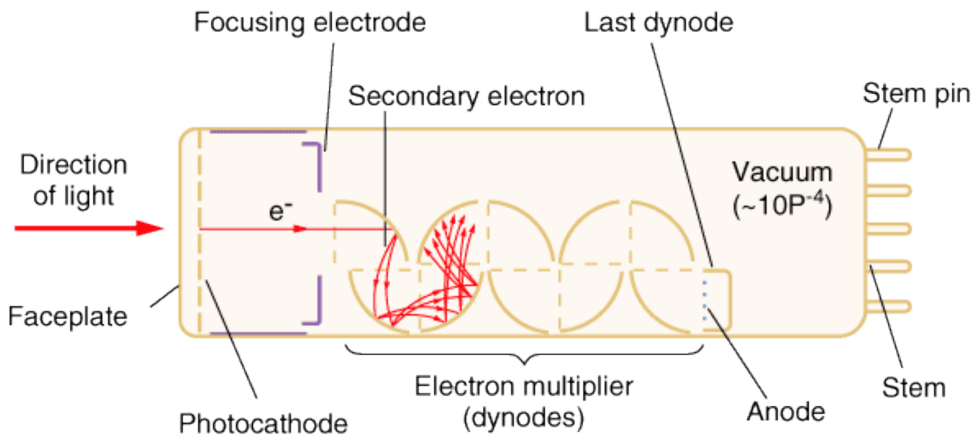
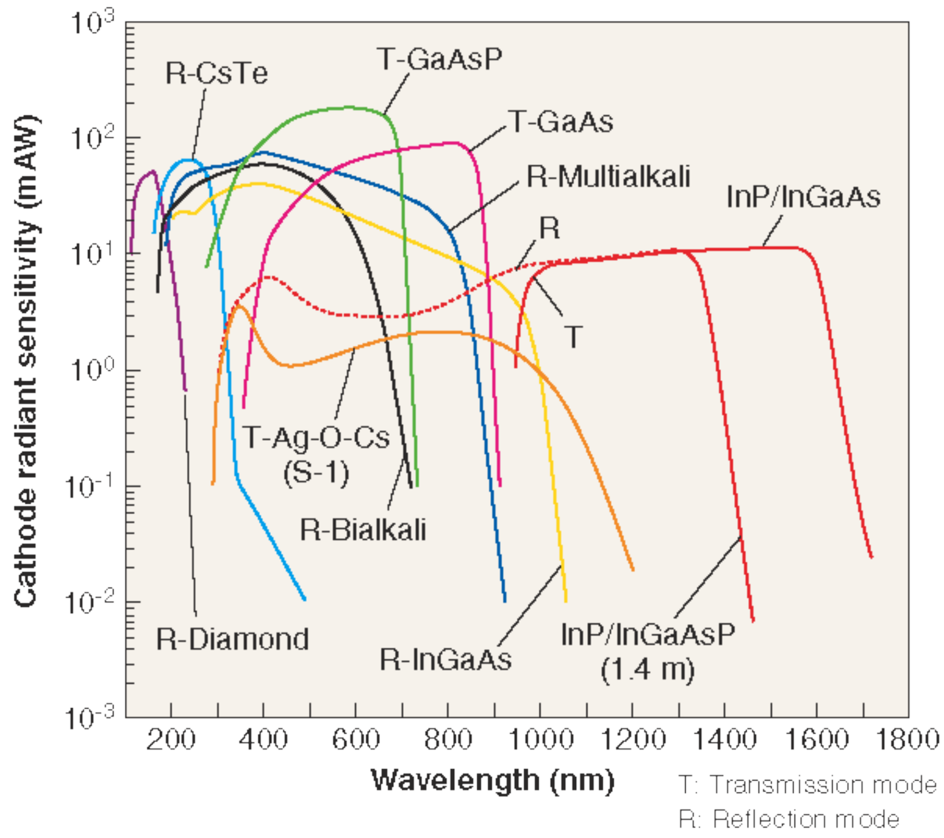


- High sensitivty (Gain ≈ 10^6)
- High time resolution (≈ 100 ps)
- Broad spectral response selection
- Photon counting possibility
- Low dynamical range
- Easily damaged (mechanical, high voltage, high irradiation)
- Bulky and need high-voltage source
- High cost



High-speed Hybrid Photodetector (HPD)

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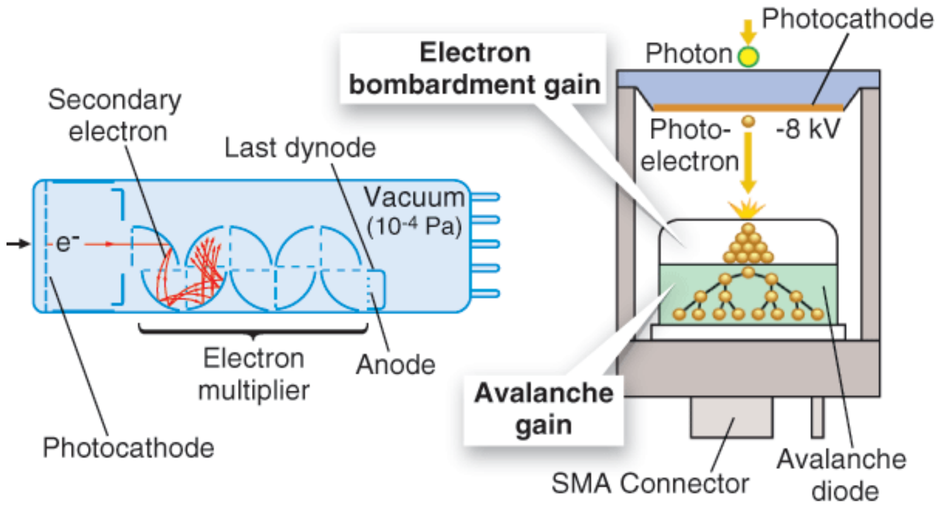

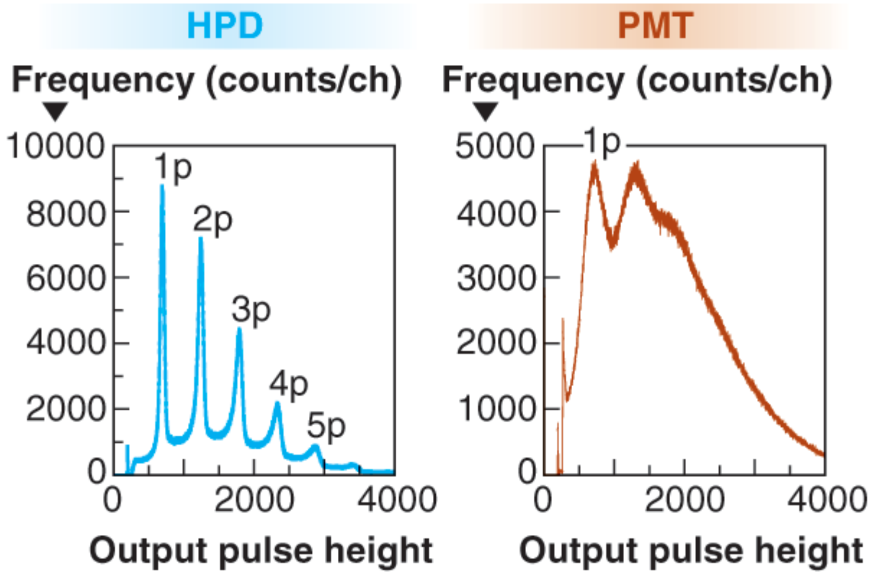

- Like PMTs, the HPD is a vacuum tube with a photocathode that reacts to light, an electron multiplier (a silicon avalanche diode) that multiplies electrons, and an output terminal that outputs an electrical signal.
- The HPD produces the signal-to-noise ratio of the electron multiplication, which in turn determines the detector's ability to differentiate between one and multiple photons.
- By using a low-capacitance avalanche diode and an electron lens with low transit time spread, the rise and fall times for a high-speed version are clocked at less than 400 ps and the timing resolution for a single photoelectron was about 50 ps FWHM.
- An afterpulse is a "false" signal generated within the detector itself. In a PMT, it can be caused by an electron escaping the dynodes and then ionizing the residual gas within the vacuum. In an HPD, however this type of interaction is minimized because its is extremely difficult for an electron to escape the avalanche diode

A. Fukasawa et al., IEEE Trans. Nuclear Sci. 55, 758 (2008).

Measurement of the detection efficiency

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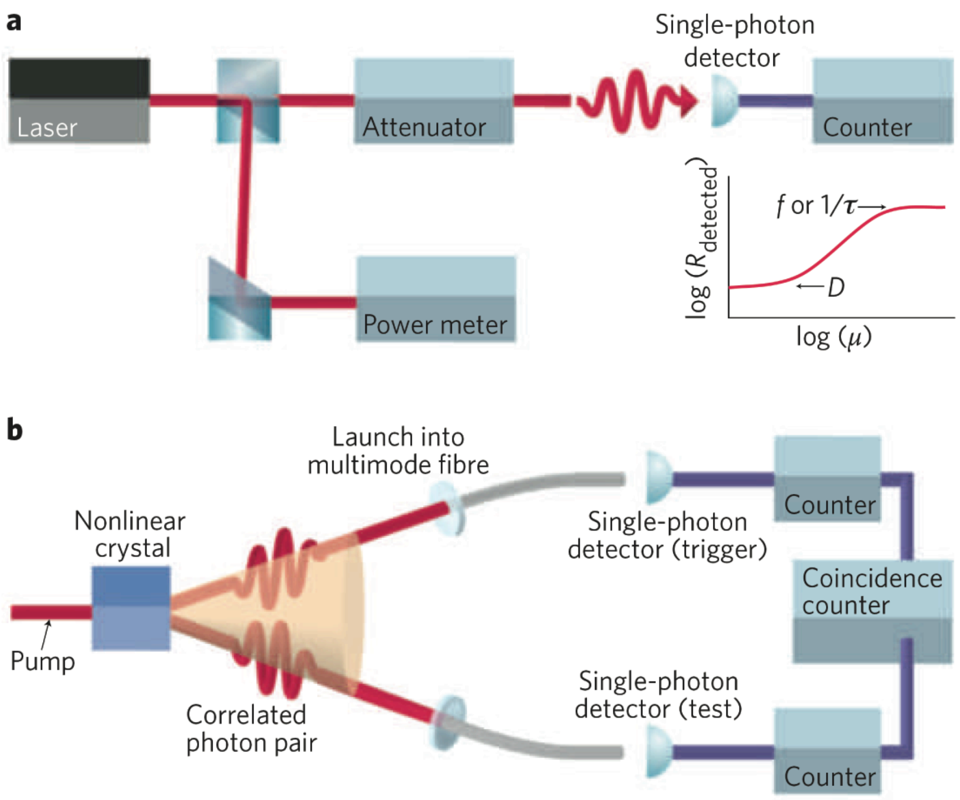
- Calibrated laser method. A continuous wave or pulsed laser is measured using a calibrated power meter. A series of calibrated attenuators are then used to reduce the photon flux μ to less than one photon per time interval. The count rate of the detector $R_{detected}$ is recorded over a range of values of μ. In the continuous-wave case, $R_{detected}$ will saturate at the inverse of the detector (or counter) recovery time, τ. In the pulsed case, saturation should occur at the repetition frequency of the laser, f. At low values of μ, the residual count rate is due to dark counts in the detector. At intermediate values of μ, the signature of a single photon detector is that $R_{detected}$ is proportional to μ.
- Correlated photon method. This method avoids the need for a calibrated power meter. A pair of correlated photon is produced from spontaneous parametric down-conversion source. The signal and idler photons are routed to the test and trigger detectors, then the respective count rates − including coincidences between the two channels − are recorded. The detection efficiency of he test detector is given by the coincidence rate divided by the count rate at the trigger detector.



R. H. Hadfield, Nature Photon. 3, 696 (2009).

Measurement of timing jitter

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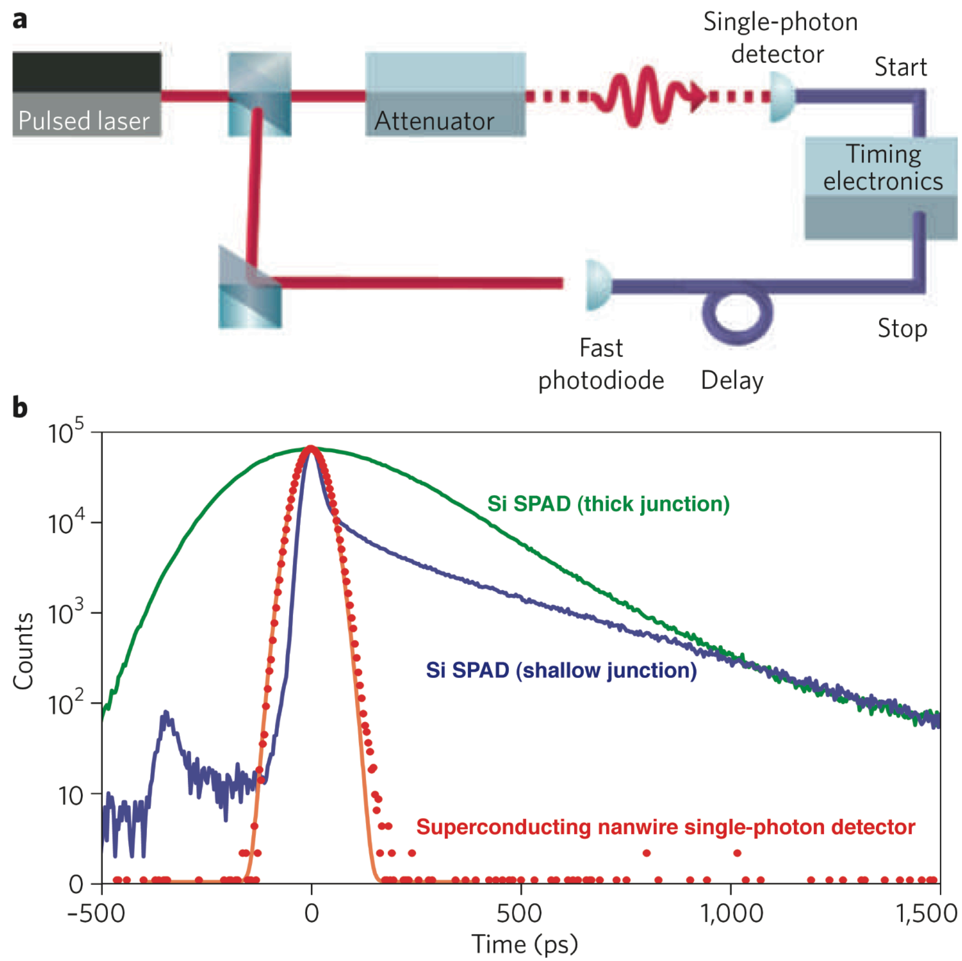
- The timing jitter of a single-photon detector is the variation in delay between the absorption of a photon and generation of an output electrical pulse.
- To measure the timing jitter accurately, a picosecond pulsed laser and high-resolution timing electronics are required to ensure that the dominant jitter is that of the detector. A count on the single-photon detector triggers the 'start' for the timing electronics, and the delayed clock pulse from the laser signals the 'stop'.
- A histogram of start-stop time intervals is accumulated over multiple clock cycles, giving the instrument response of the single-photon detector.



R. H. Hadfield, Nature Photon. 3, 696 (2009).
M. J. Stevens et al., Appl. Phys. Lett. 89, 031109 (2006).

Detector-selection flow chart

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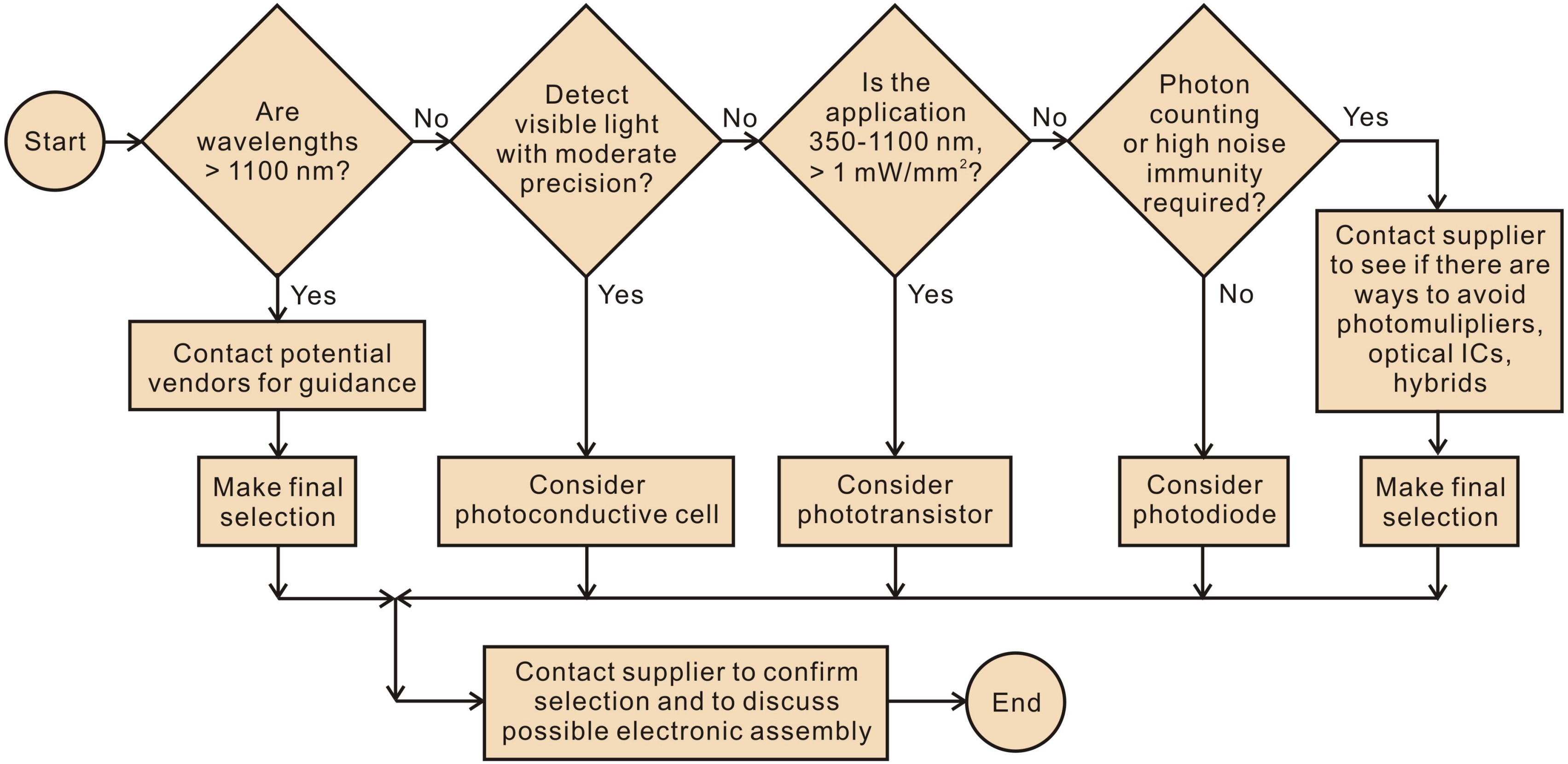

Charge-coupled devices (CCD)

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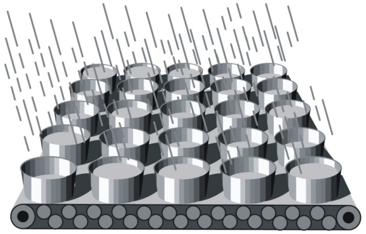


Figure 1. *The pixels of a CCD collect light and convert it into packets of electrical charge.*

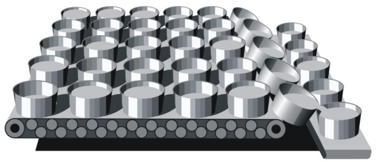


Figure 2. *The charges are quickly moved across the chip.*

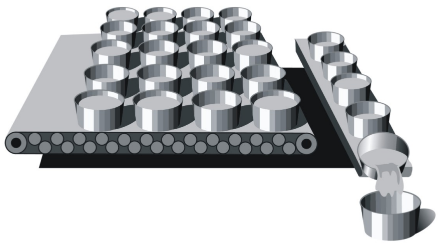
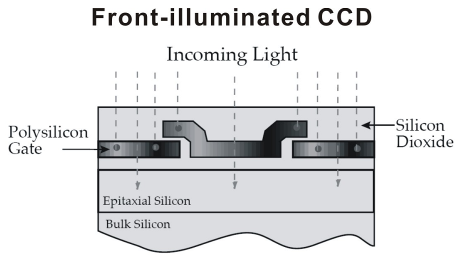
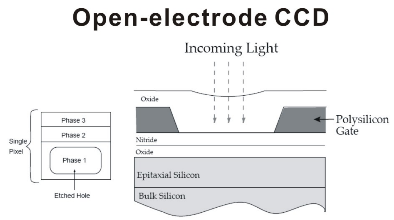
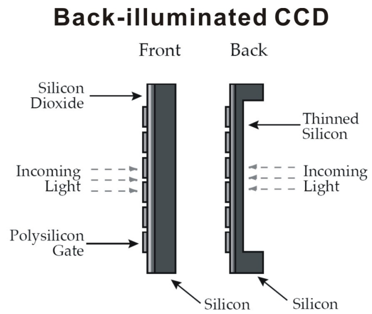


Figure 3. *The charges are then swept off the CCD and converted to analog electrical impulses, which are then measured as digital numerical values.*







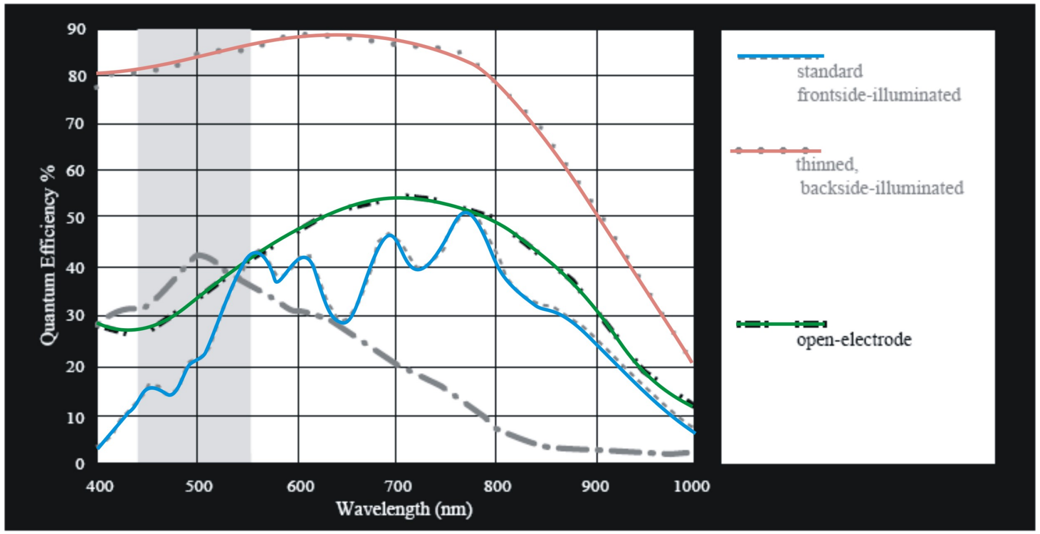


Image intensifiers

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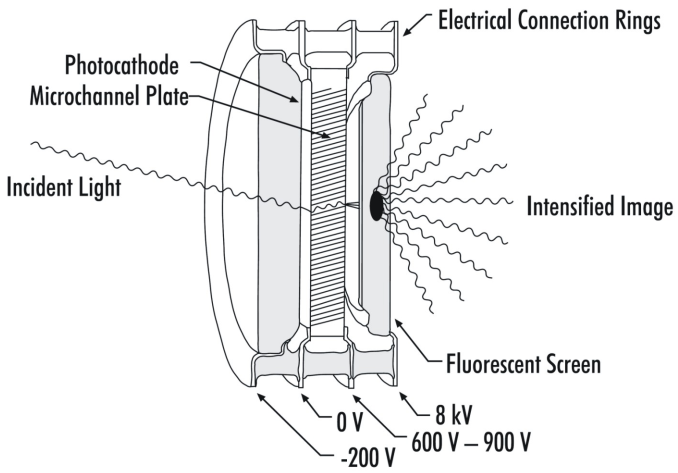
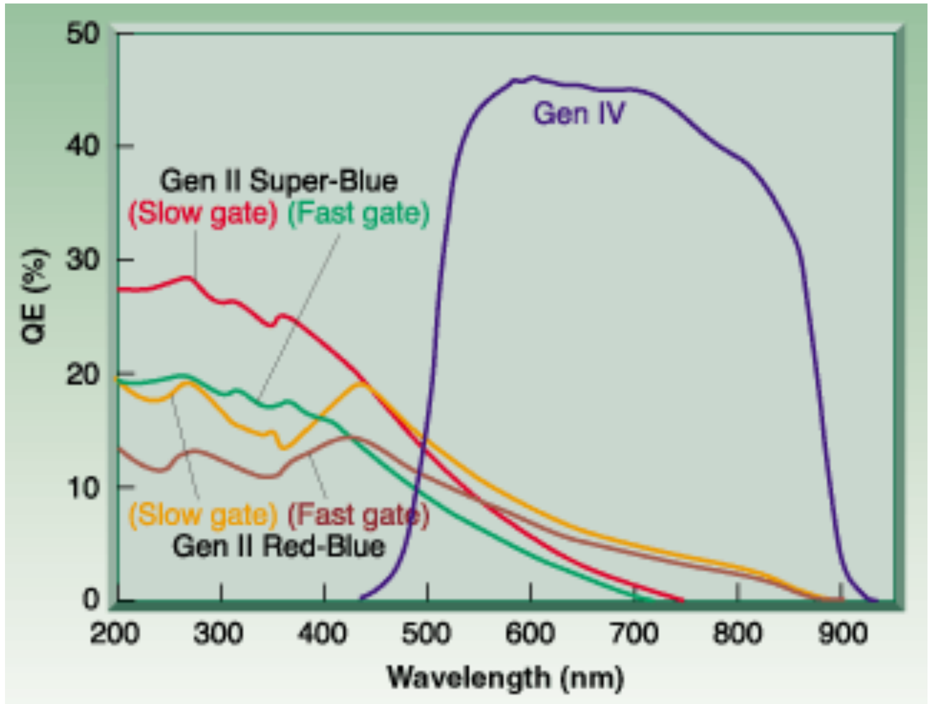
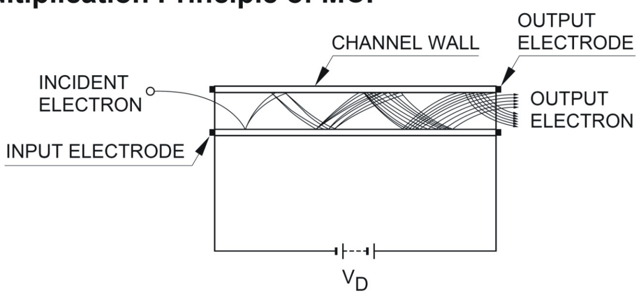




Multiplication Principle of MCP



Electron multiplying CCD

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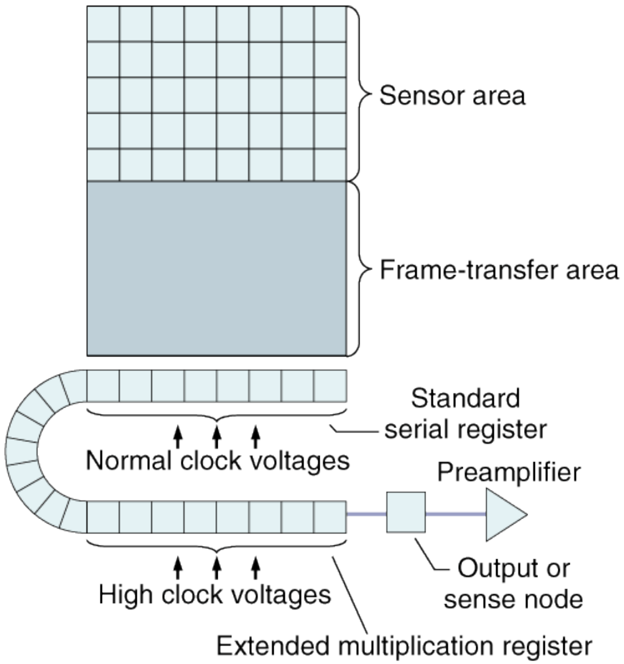
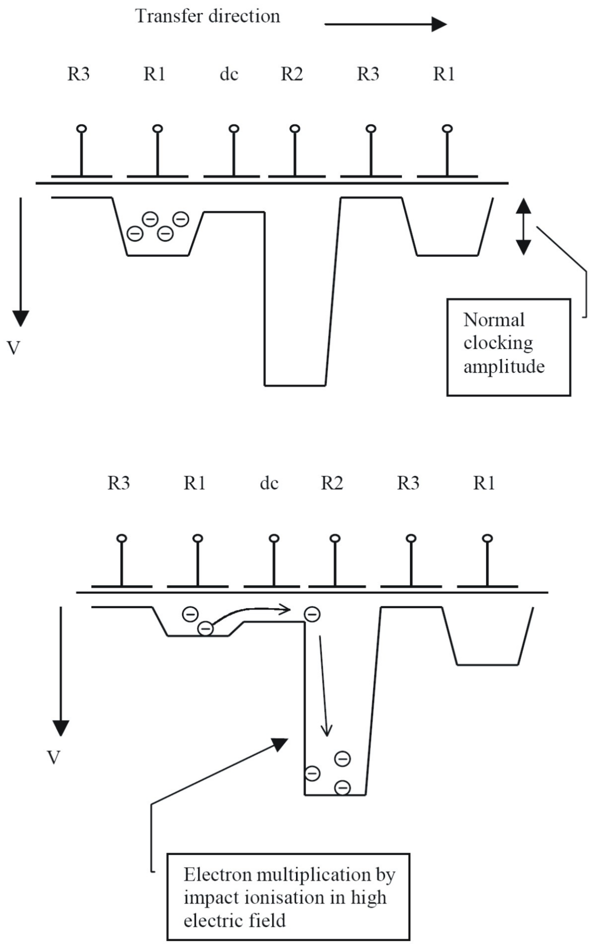
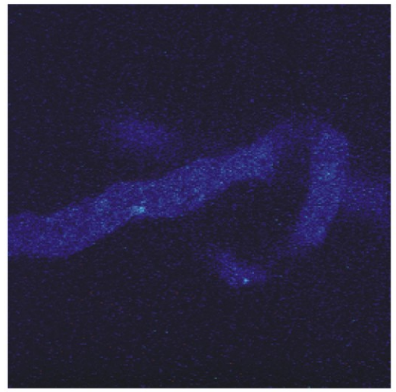
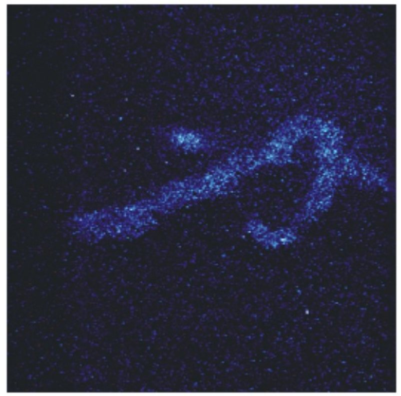




BV-EMCCD



GenIII+ ICCD



Michelson interferometer

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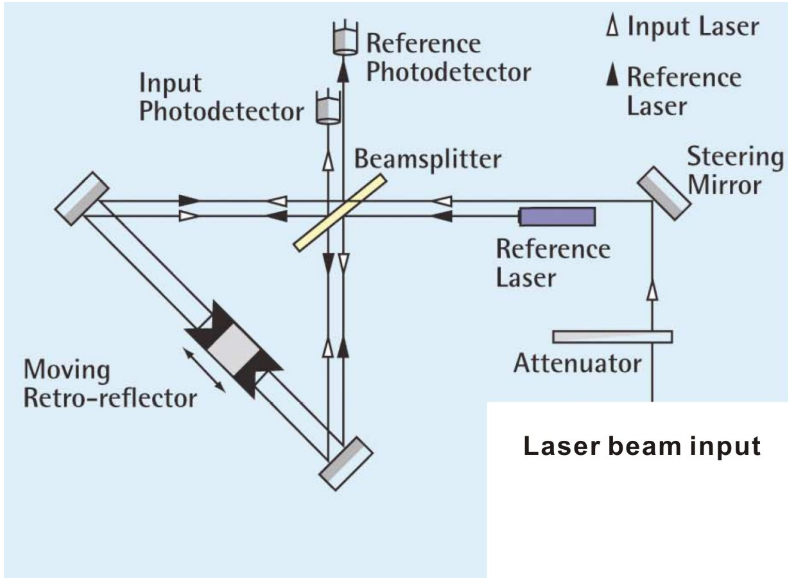
- Michelson interferometer is used in investigations that involve small changes in optical path lengths. With the Michelson interferometer, one can produce circular and straight-line fringes of both monochromatic light and white light. One can use these fringes to make an accurate comparison of wavelengths, measure the refractive index of gases and transparent solids, and determine small changes in length quite precisely. The instrument can be used as a stable mode selecting resonator element in laser cavities as well.
- The absolute wavelength of a laser can be determined by comparing its interference fringe pattern with that of a built-in reference laser (frequency-stabilized HeNe laser) wavelength standard.
- The wavelength of a test laser is determined by

$$\lambda_{test} = \left(m_{HeNe}/m_{text}\right)\times\left(n_{test}/n_{HeNe}\right)\times\lambda_{HeNe}$$

  m_{HeNe} and m_{test} are fringe numbers for HeNe and test laser, respectively. n_{HeNe} and n_{test} are refractive indices for HeNe and test laser wavelengths, respectively.
- The wavelength accuracy can reach ±0.2 ppm.



Wavelength meter

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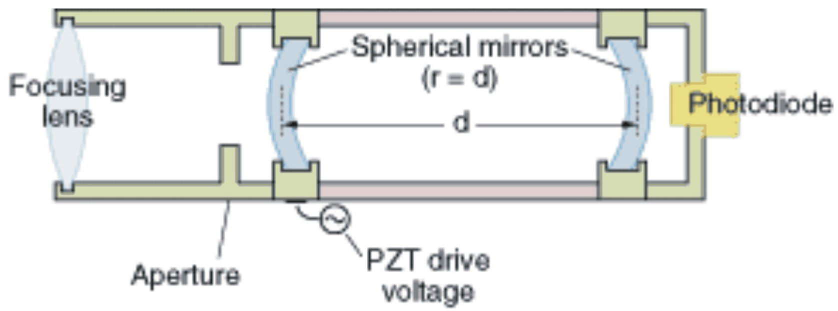
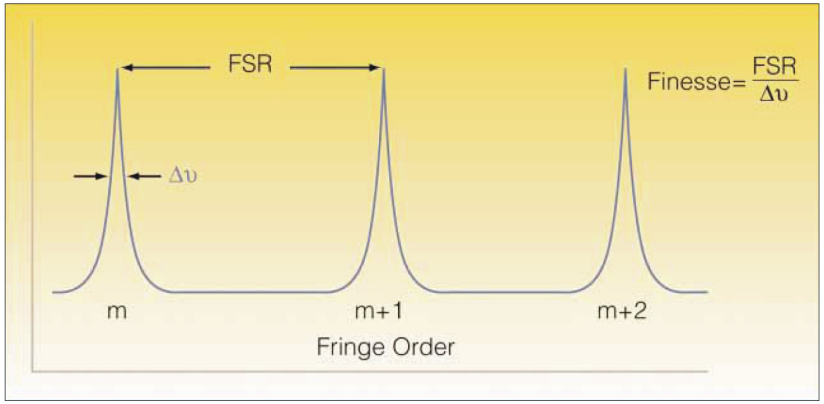
- Fabry-Perot interferometer consists of a cavity formed by two parallel, concave, and highly reflective mirrors. When an integral number of incident half-wavelengths resonate inside the cavity, it becomes highly transmissive. One of the mirrors is scanned by a piezoelectric transducer (PZT) to search for resonant wavelengths.
- One disadvantage of such a device is that, because different integer values can meet the resonant-cavity criterion, the same wavelength may appear multiple times as separately detected signals. The range of frequency that the interferometer can cover without duplicating a wavelength is called its free spectral range (FSR) (< 10 GHz or 0.3 nm). The resolution of this instrument is determined by the reflectivity of its mirrors and their separation. Resolution appears in a figure of merit called "finesse," which is the FSR divided by the resolution. These instruments can resolve linewidths of less than a picometer.



Fabry-Perot Interferometer



Transmission pattern

Monochromator

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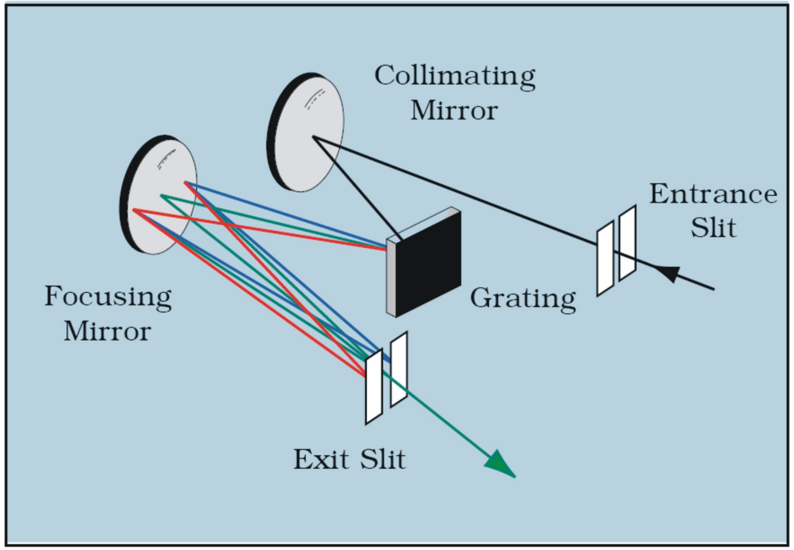
- Monochromator is an "optical instrument" designed to separate polychromatic "white light" (light consisting of more than one color or wavelength) into monochromatic light (light of a single color).
- Light enters the entrance slit and is collected by the collimating mirror. Collimated light strikes the grating and is dispersed into individual wavelengths. Each wavelength leaves the grating at a different angle and is re-imaged at the exit slit by the focusing mirror. As each wavelength images at a different horizontal position, only the wavelength at the slit opening is allowed to exit the monochromator. Varying the width of the entrance and exit slits allows more (or fewer) wavelengths to exit the system. Rotating the diffraction grating scans wavelengths across the exit slit opening. Monochromatic light can be used to illuminate a sample, or it can be scanned across a detector and measured for intensity at individual wavelengths.



Spectrograph

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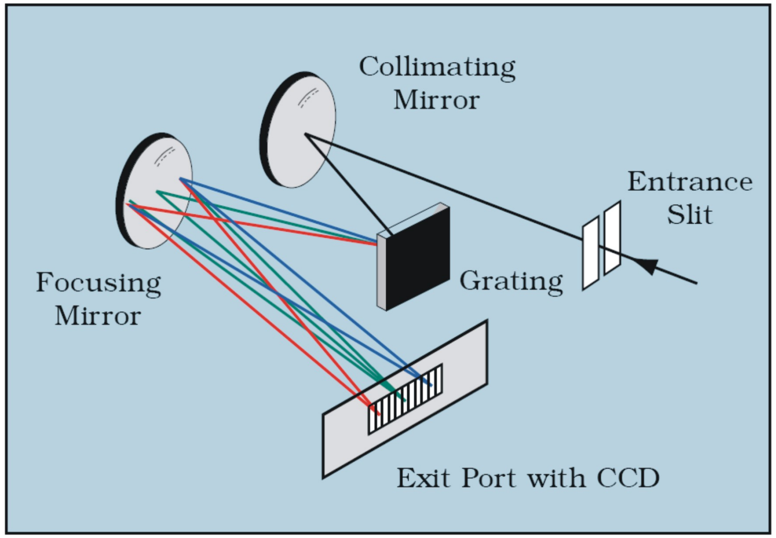
- Spectrograph is similar to monochromator, except that in place of the exit slit, an array detector such as a CCD is positioned. Individual wavelengths focused at different horizontal positions along the exit port of the spectrograph are detected simultaneously by the array detector.
- The spectral resolution of a spectrograph states ability to resolve multiple closely spaced wavelengths. It is a function of the dispersion of the spectrograph, usually stated in nanometers per millimeter, and the imaging quality of the optics. The dispersion figure depends on the groove density of the grating and the focal length of the spectrograph.
- The aperture of a spectrograph defines its ability to gather light into the instrument. The larger the aperture, the more light can be directed to the detector, thus improving the throughput or sensitivity of the spectrographic system. Aperture is usually stated as *f/#* number, which is a measure of the ratio of the focal length to the diameter of the smallest optical element in the system.



Considerations in choosing spectrometers

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- Grating equation:

  $$\sin\alpha + \sin\beta = 10^{-6} kn\lambda$$

  k is the diffraction order, *n* is the groove density, λ is the wavelength.

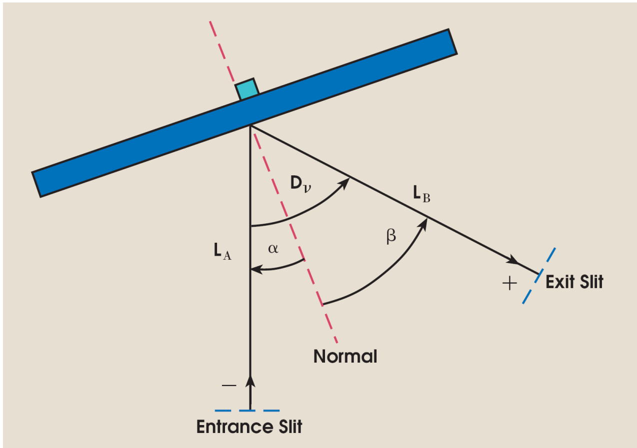
- Dispersion, resolution and bandpass: The dispersion ($d\lambda/dx$) shows the capability to disperse light. It gives the usable bandpass of a monochromator or indicates the spectral range of a spectrograph equipped with a multichannel array detector such as a CCD. Changing the width of the slit aperture can adjust the bandpass. If the application's most important requirement is to acquire a large spectral range in one shot, small spectrograph are better.

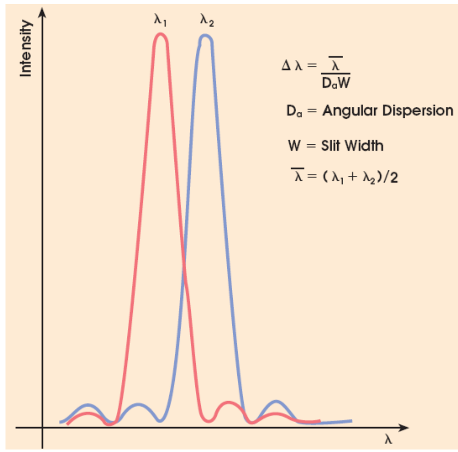
- Throughput and image quality: A useful fiture of merit for comparing monochromators for throughput and image quality if light-gathering capability (LGC). It is defined as below.

  $$LGC = \frac{height_{slit}(mm)}{(f/\#)^2 \times dispersion(nm/mm)}$$

  The imaging spectrographs which use toroidal gratings or mirrors to correct astigmatism in the image plane and to improve image quality.

- Stray light relates mainly to the quality of the device's optical components (mirrors and grating). When the stray light is important in an application (such as Raman spectroscopy), large focal-length instruments or double monochromators are the best choise.





Laser beam profile analysis

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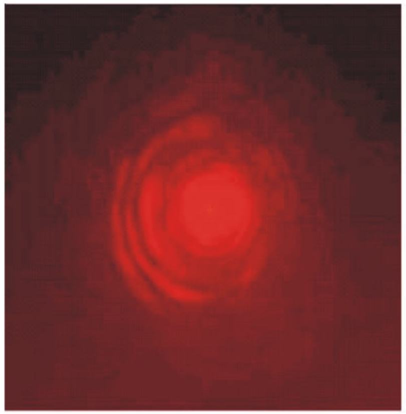
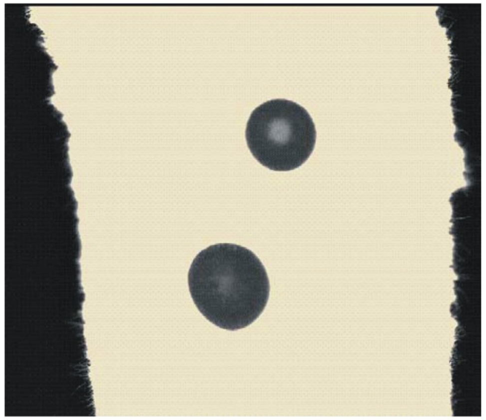
Non-electronic methods

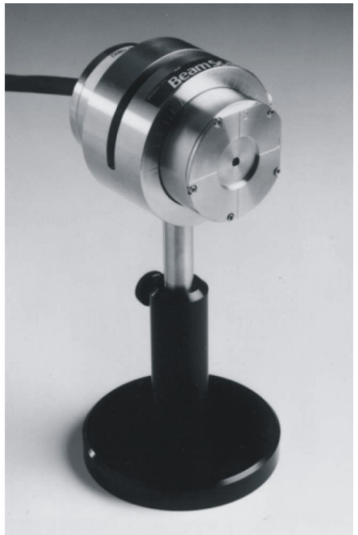


Reflected beam



Burn spots

Electronic methods



Scanning knife-edge

Array detector

Laser beam profiles

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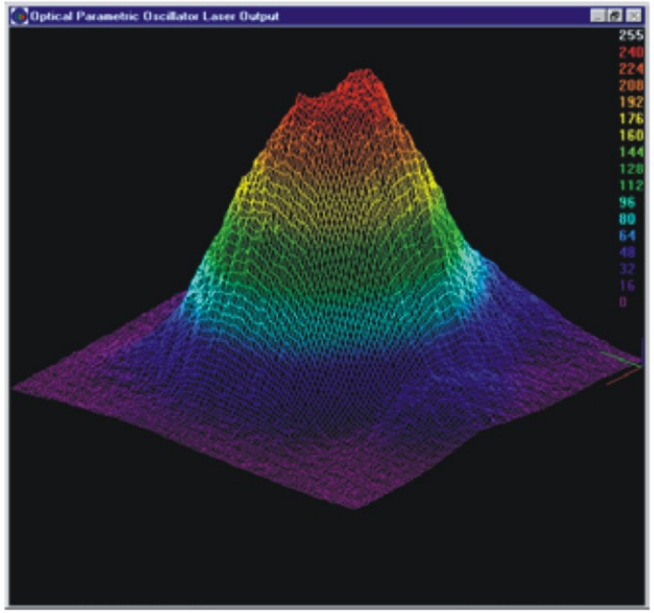
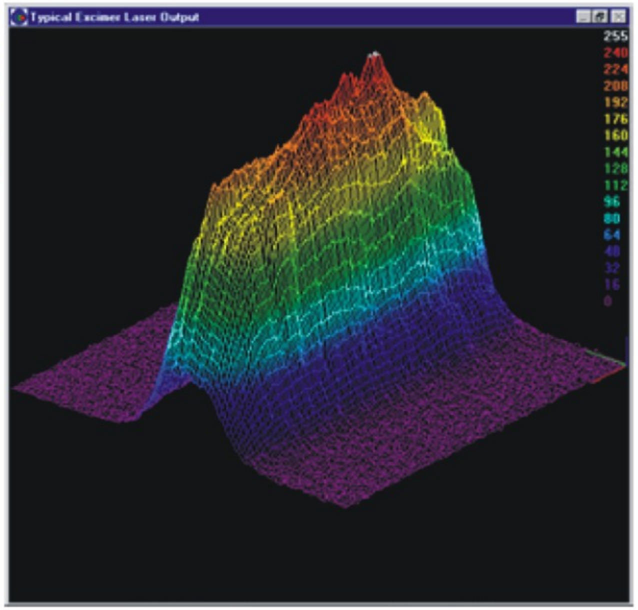
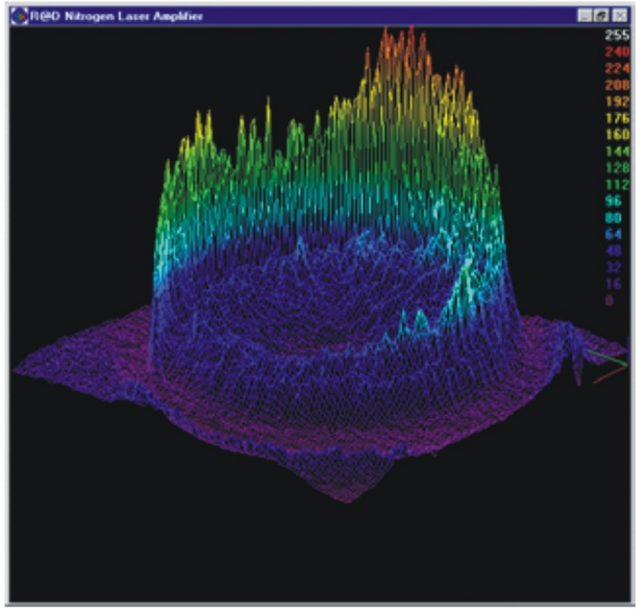


HeNe laser



Excimer laser



Nitrogen laser

M^2 measurement

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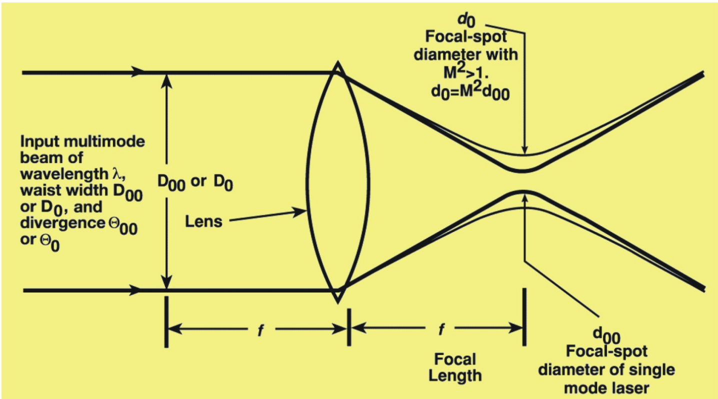

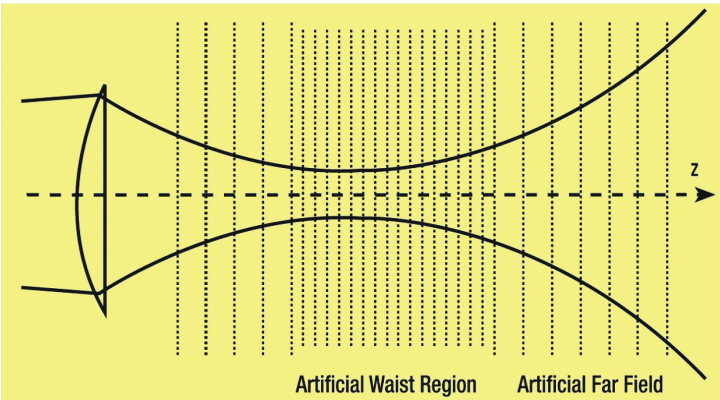

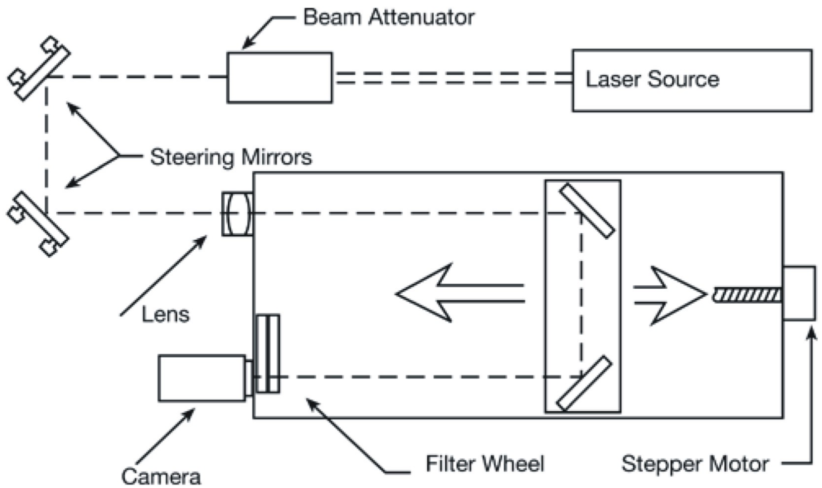

$$d_0 = M^2 4\lambda f / \pi D_{in}$$

D_{in} : the beam waist width of the input beam

Laser pulse width measurements

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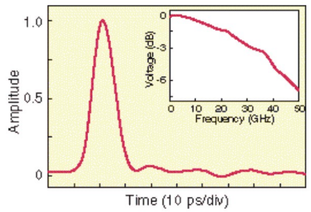
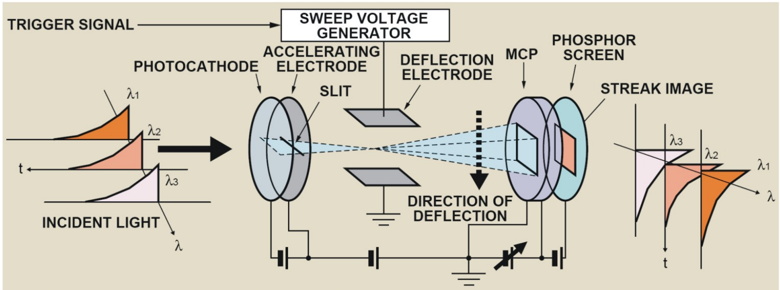
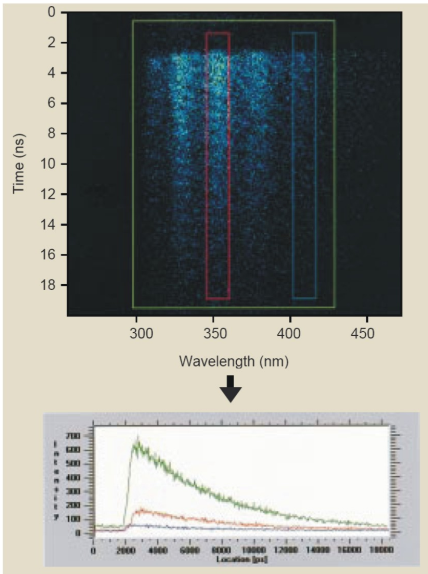
Photodiode (> 6 ps)

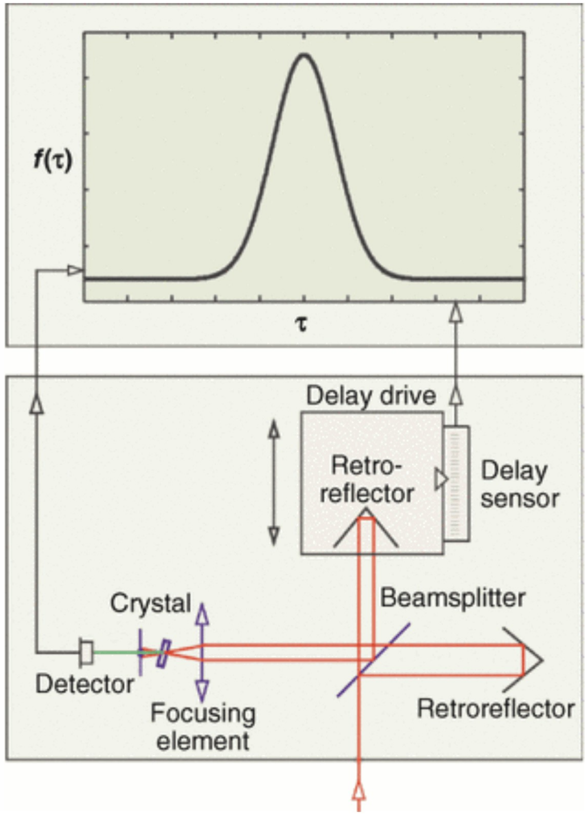


Streak camera (> 300 fs)





Autocorrelator (> 1 fs)



Amplitude and phase retrieval

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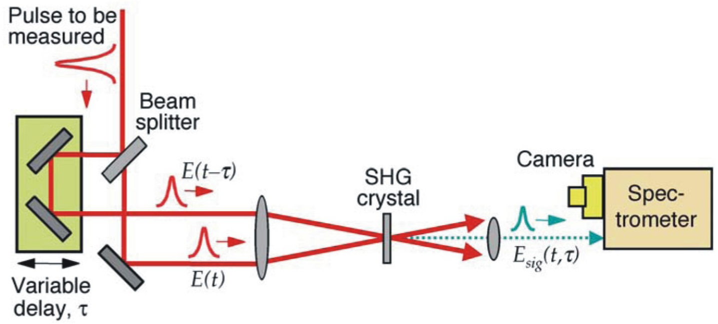
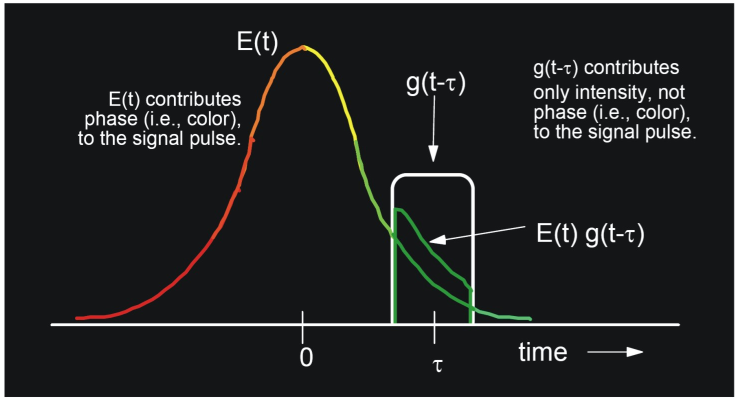
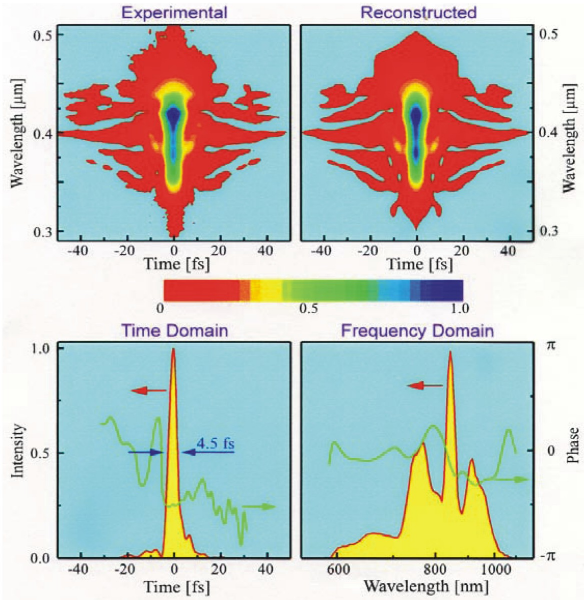


$$\Sigma_g(\omega,\tau)=\left|\int_{-\infty}^{\infty}E(t)g(t-\tau)\exp(-i\omega t)dt\right|^2$$





General rules for signal averaging

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- General statements: Signal-to-Noise Ratio (SNR) is impoved by square root of number of samples.
- Rule #1: Measurement must be independent, uncorrelated.

  - Realistically, complete independence impossible to achieve because of exponential nature of signal change in time.

  - For a single time-constant system, spacing data sampling interval by one time constant improves SNR by $(N/2)^{1/2}$ and not $N^{1/2}$.

  - No prohibition to faster sampling; but the correlation of such measurements reduces the apparent gain in SNR.

  - Maximum SNR improvement is proportional to square root of observation time, independent of sampling rate.
- Rule #2: Signal must be stationary.

  - If there is a low frequency drift (1/f noise) in the data, normal statistical analysis may be compromised, and further analysis is mandatory.

  - The higher the drift rate (higher 1/f noise component compared to the white noise component), the shorter the sampling or integration time and the lower the achievable SNR.

  - If you have drift, use regression analysis (linear, exponential, power etc.) to fit a curve the data. (You may have to low-pass filter the data to reduce the random noise first to get a good fit.

Signal bandwidth (B) considerations

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- Compromises for information content:

  - Looking for just magnitude requires small bandwidth.

  - Recovering waveform requires large bandwidth.
- SNR increases as ~1/√B for white noise. The SNR increase is thus ~$\sqrt{B_{in}}/\sqrt{B_{out}}$.
- Nyquist criterion:

  - For signal fidelity with no aliasing, signal bandwidth must be at least twice the highest frequency component in the signal.
- For rectangular pulses of equal amplitude, the bandwidth must be at least (twice the pulse width)$^{-1}$.
- If a chopper is used in a lock-in detection scheme, its frequency should be at least three times the highest frequency component in the signal.
- For an inaccuracy of 5% in a lock-in detection scheme, the settling time must be two times constant (t), where t is $1/(2pf_c)$, where f_c is the -3dB bandwidth of the signal. For 1%, wait 5t; for 0.1%, wait 7t.

Signal bandwidth reduction

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- Software techniques to enhance SNR on an existing data set
- Hardware base-band (dc) filtering (low-pass)
- Hardware analog filters (high-pass, bandpass, band reject)
- DSP filter (adaptive, etc.)
- Waveform analyzer (tunable bandpass filter)

Averaging or integration techniques

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These require a repetitive or periodic reference signal, synchronous with the signal.

- Lock-in amplifier (synchronous detector, phase-sensitive detector)
- Boxcar (gated integrator)
- Multi-point signal averaging.

Lock-in amplifier

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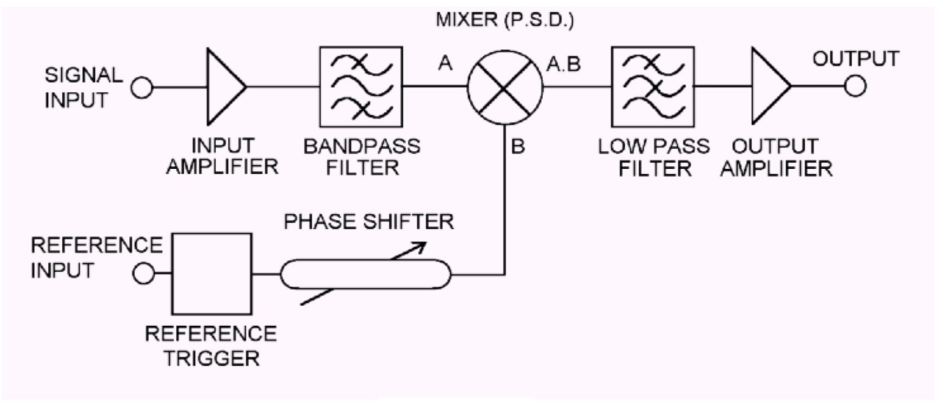
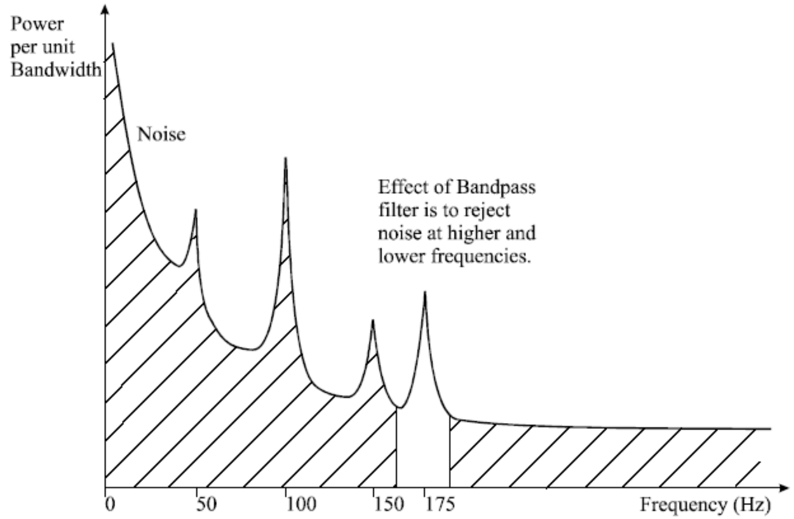
- A lock-in amplifier is basically a narrow band filter. The center frequency of the filter is determined by a reference which modulates or "chops" the signal of interest. The modulated signal is fed through the filter and the rectified output is smoothed by an RC integrator with a variable time constant.
- It is a homodyne detection scheme whereby signal mixed with reference (in-phase, at same frequency).
- Output of PSD (phase-sensitive detector): $E_{PSD} = (E_{SIG}E_{REF}/2)\cdot[\sin(2\omega t+\phi)+\sin\phi]$. The last term is desired DC component. Use low-pass filter to eliminate all high frequency terms.





BOXCAR (gated integrator)

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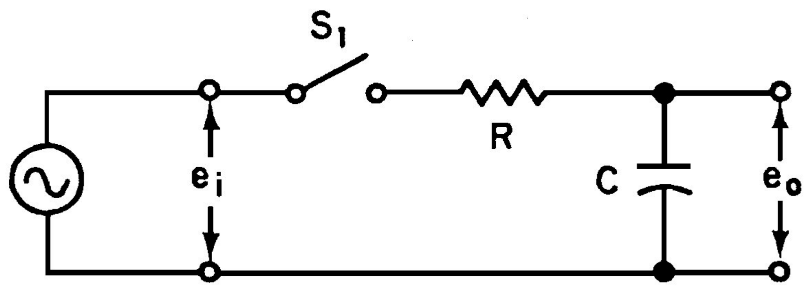
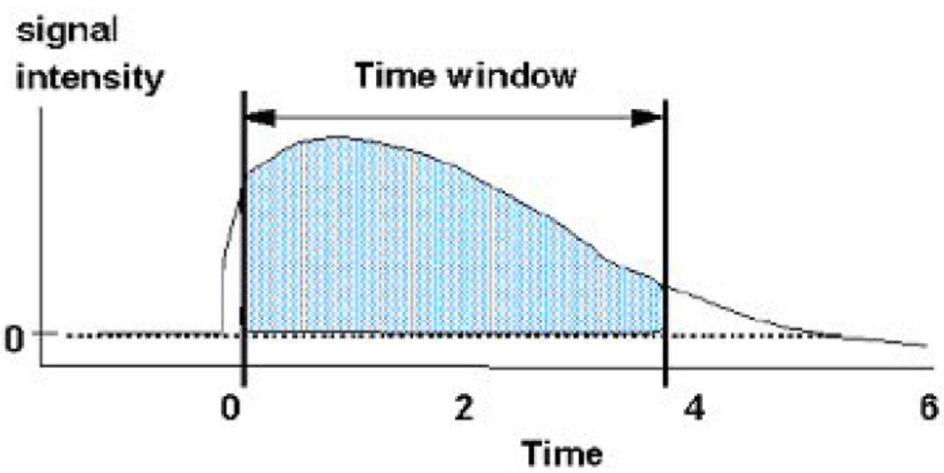
- Place a window in time domain that corresponds with presence of signal, excludes noise outside of window. SNRI = $\Delta t_{cycle}/\Delta t_{gate}$.
- Integrator (= low-pass filter) accumulates charge only when gate on.
- If gate is small and its delay is ramped, can reconstruct input waveform.





Multi-point signal averaging

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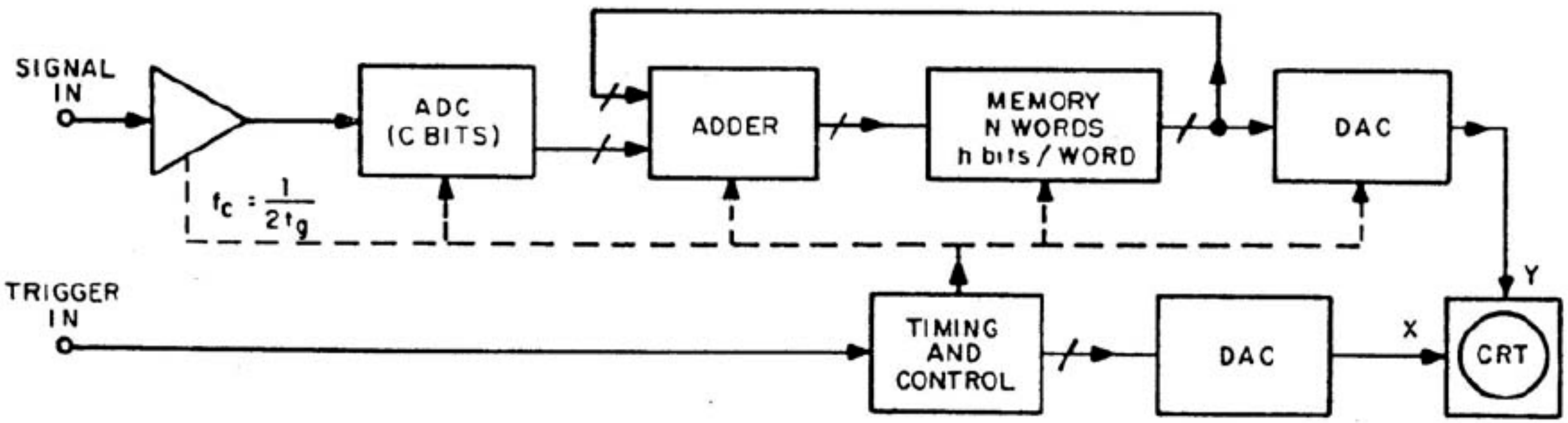
- In response to trigger, series of samples taken on waveform; stored in N memory cells.
- Subsequent samples are added to early ones and averaged.
- Signals build up, noise averages toward zero. SNRI = (number of sweeps)$^{1/2}$.
- Each sweep must be nominally the same, takes some time, diminishing returns for large number of sweeps.



Other signal processing techniques

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- Autocorrelation (signal with itself)
- Cross-correlation (match signal with desired pattern)
- Optical techniques:
  - Photon counting technqiues (requires sampling rate <100 MHz)
  - Homodyne detection
  - Heterodyne detection

Photon counting

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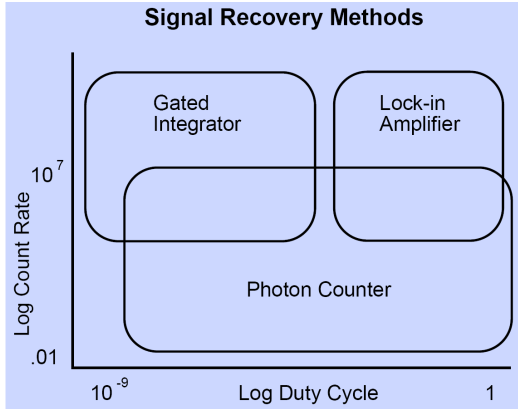
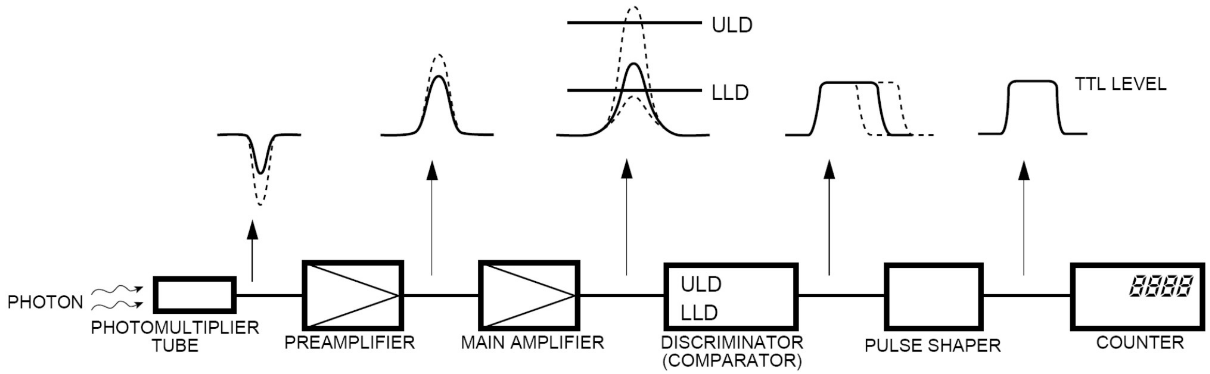
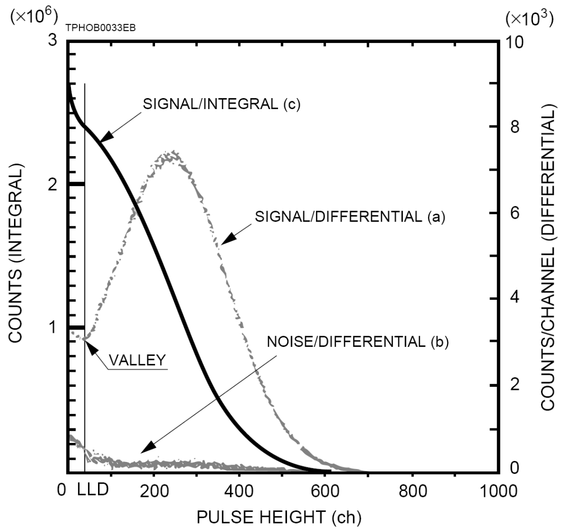
- Photon counting: Counting photons one by one.
- PMT or APD is used to detect photons. A discriminator then discriminates signal photons from noise photons according the pulse-height distribution. The resultant TTL pulses are then counted by a counter.
- Dark counts should be as little as possible.
- The photodetector is operating in gain saturation region.
- Pulse width and transit time should be as short as possible.
- After pulsing effect.







Homodyne and heterodyne detection

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- Consider two optical beams mixed on a photodiode (square-law detector).

$$I \sim \left| E_{SIG} + E_{OSC} \right|^2$$

$$= \frac{E_r^2}{2}\left[1+\cos^2\left(\omega_r t+\phi\right)\right] + E_r E_0 \left\{\cos\left[\left(\omega_r-\omega_0\right)t+\phi\right]+\cos\left[\left(\omega_r+\omega_0\right)t+\phi\right]\right\} + \frac{E_0^2}{2}\left[1+\cos^2\left(\omega_0 t\right)\right]$$

- Homodyne detection:

  - w_r is set to w_0.

  - Apply low-pass filter to remove high frequency components.

$$I \sim \frac{\left(E_r^2+E_0^2\right)}{2} + E_r E_0 \cos\left(\phi\right)$$

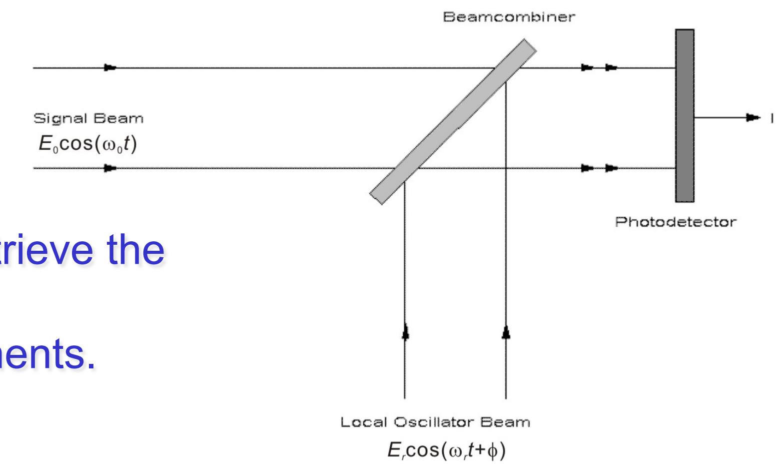
- Heterodyne detection:

  - w_r is not equal to w_0.

  - Use another in-phase electronic oscillator (w_r-w_0) to retrieve the signal at w_r-w_0.

  - Apply low-pass filter to remove high frequency components.

$$I \sim E_r E_0 \cos\left(\phi\right)$$



Initial concept

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- What are the optical techniques needed for the experiments?
  - What information need be acquired or what effect need be generated?
  - Is it possible to use the existing optical techniques to acquire such information or to generate such effect?
  - If not possible, can a new optical technique be developed?
  - How is the detected signal connected to the acquired information or the generated effect quantitatively? That is, can a mathematical expression be derived?
- What are the required instruments and components for the experiments?
  - What are the required light sources?
  - What are the required optical and opto-mechanic components?
  - Is good vibration isolation necessary? How good does it need to be?
  - Is motion control needed? If yes, what kind of motion control is needed?
  - What is the detection scheme (detectors and detection methods)?
  - What are the signal processing scheme?

Computer drawing

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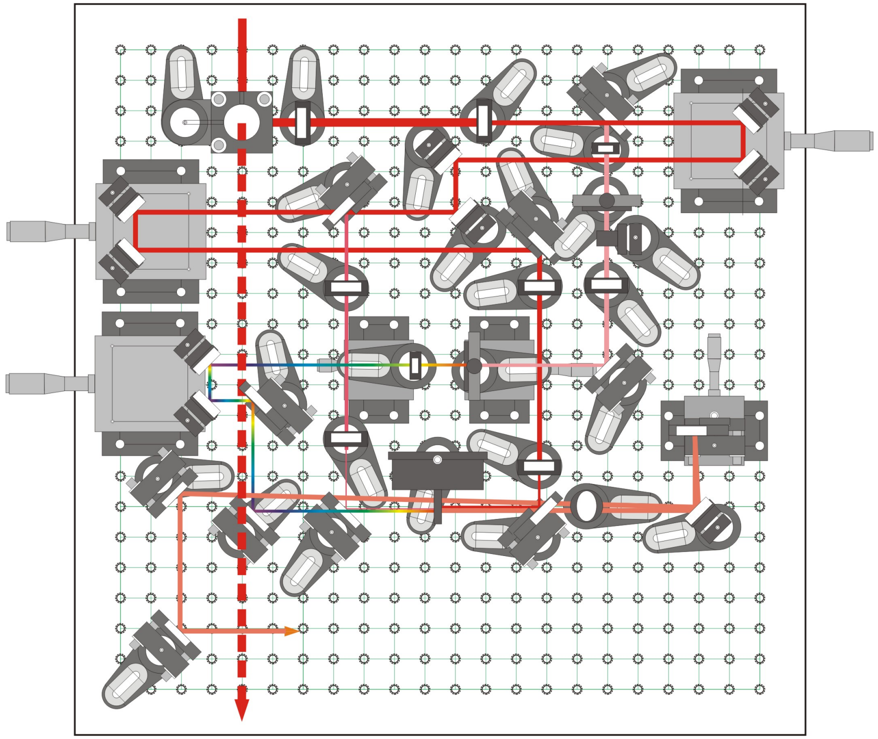
- Computer drawing is a necessity to convert an initial concept to an experimental setup without any try-and-error.
- Search for the most suitable components
- Custom design
- All optical and opto-mechanic components need to be in the drawing with accuracy of 1 mm.
- Both top- and side-view drawing are needed.
- Ray-tracing analysis is needed, if necessary.
- More complicated simulation (including electromagnetic wave propagation, light-matter interaction, etc.) can be further incorporated if necessary.



Revision

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- Is there any consideration missing in the design?
  - Review the design from the beginning to the end and try to consider every detail
  - Try not to put some thing into the consideration later on, because it may be forgotten
  - Do not just think about optics (electricity, air conditioning, lighting, vacuum system, etc.)
  - Arrange necessary iris diaphragms in the set up
- Can the design be further simplified?
  - Check the degree of freedom of motion on each opto-mechanic component
  - Do not use unnecessary optics (mirrors, iris diaphragm, etc.)
  - Try to come up a custom design to replace a complicated assembly built with stock items
  - Try to shrink the size of the optical layout (the bigger the size is, the more unstable the optical alignment is)
- Can the total cost be reduced?
  - Is the expensive component really necessary?
  - What is the actual required specification of each component?
  - The more careful the design consideration is, the more likely the cost can be reduced.
- Does the optical setup need to be mobile and enclosed?
  - Put an optical setup which has clear input and output in an enclosed box
  - Enclosed box can prevent unnecessary laser scattering and minimize environmental lighting
  - Check the required rigidity of the enclosed box
- Is the whole design beautiful?
  - Check the balance of the whole design
  - Check whether each component is closely related with other components

Construction

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- Make a construction plan
  - Purchasing parts and components
  - Custom design
  - Lay out the time schedule
- Test each component and subsystem before assembly
- Optical alignment
  - Define the optical axis
  - Arrange check points
  - Isolate independent subsystems

Remind of course requirement

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- A construction plan for an optical setup (50%)
  - It should contain a computer drawing, a purchasing list of parts, and a report.
  - The design should be composed of light source(s), optical and opto-mechanic components, and detector(s).
  - Both top and side views of the drawing should be provided. It should be laid out on a breadboard or an optical table. An example of computer drawing is given in the lecture.
  - The list of parts should contain specification which describe the important information why they are chosen.
  - **The total number of items (optic and opto-mechanic components) should be more than ten. Jointed effort by several people is encouraged. However, the number of components will be added up**.
  - The grade will depend on its innovativeness, completeness, and functionality.
  - A one-page proposal (10%) needs to be submitted to teaching assistants (TAs) before **March 27**.
  - A final report (40%) needs to be submitted to TAs before **April 30**.
- A hand-on experiment of Twyman-Green interferometer (30%)
  - A note will be released by TAs before May 19. The lab time will be arranged with TAs.
  - Each student will be asked to measure the refractive index of an unknown right-angle prism.
  - On **April 10**, in-lab evaluation (20%) on the optical alignment procedure will be performed. Each student has 15 minutes to complete the alignment.
  - A final report (20%) needs to be submitted to TAs before **April 30**.
- Class attendance (20%)
  - The attendance rates in lectures and assigned experiments are accounted for in the grading.

Key elements in laser ablation

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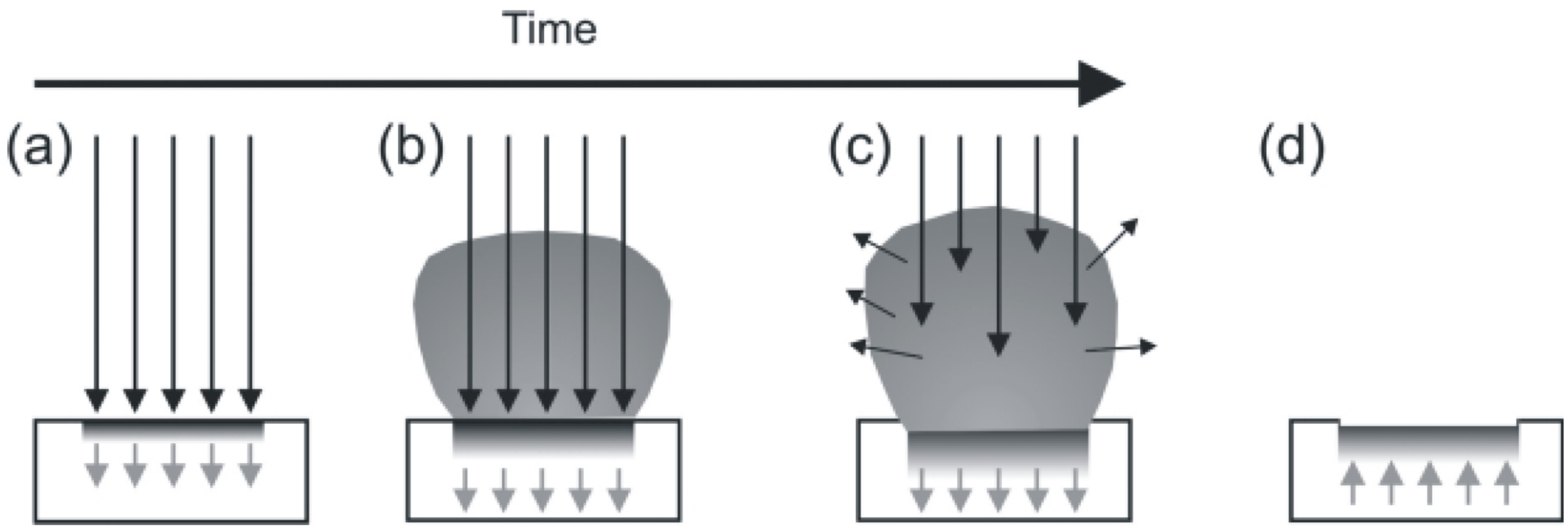

Laser absorption
Melting
Vaporization

Melt front propagation
Vaporization
Laser-plume interaction

Laser absorption by plume
Plasma formation

Melt front receding
resolidification

Microscopic view of laser ablation

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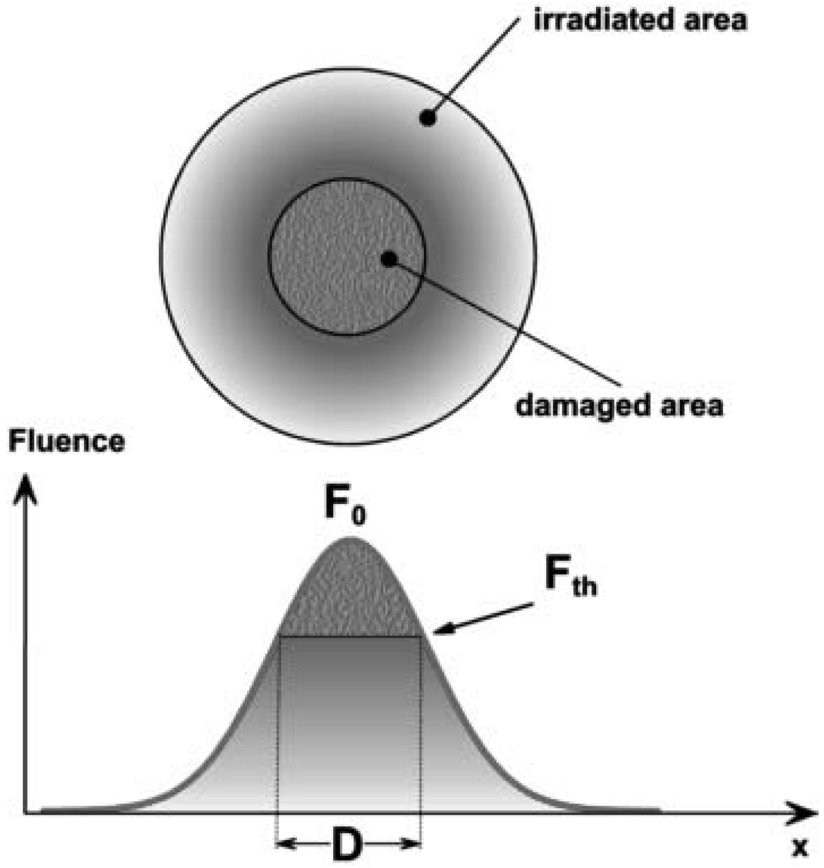

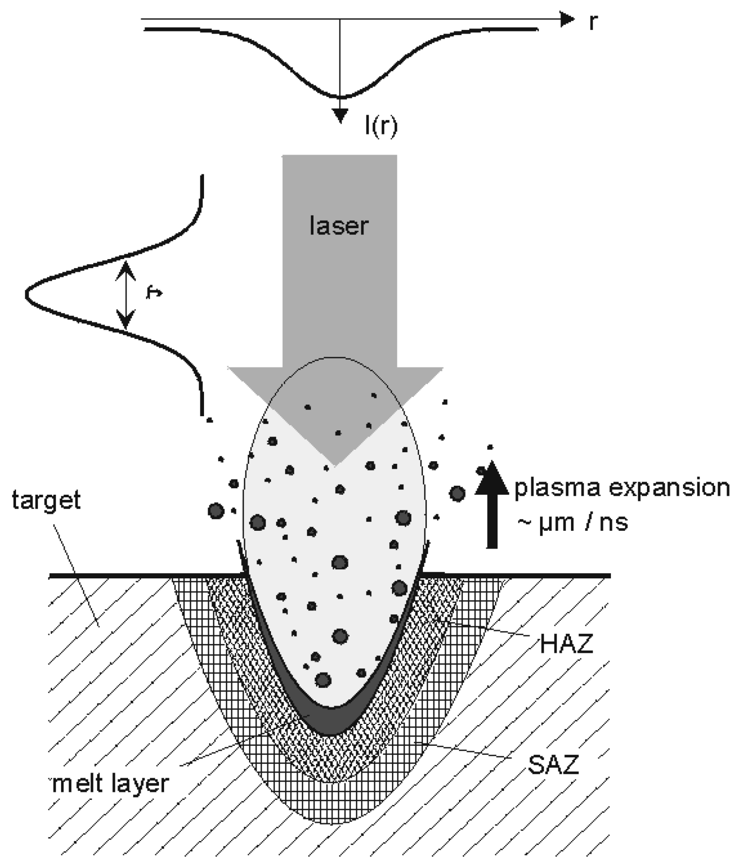

J. Kruger and W. Kautek, Adv. Polym. Sci. 168, 247 (2004).

Surface morphology after ablation

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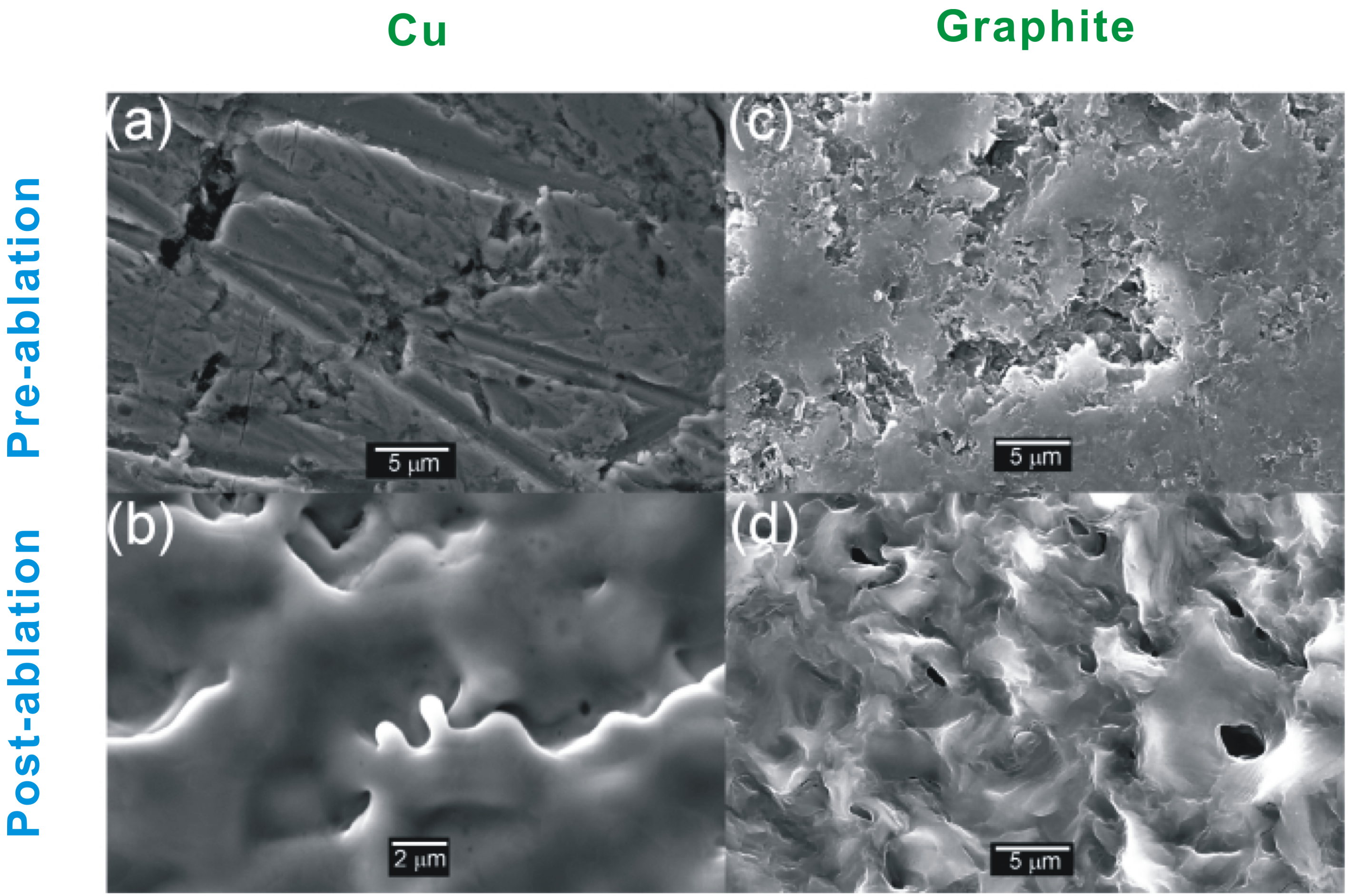

Hole drilling through laser ablation

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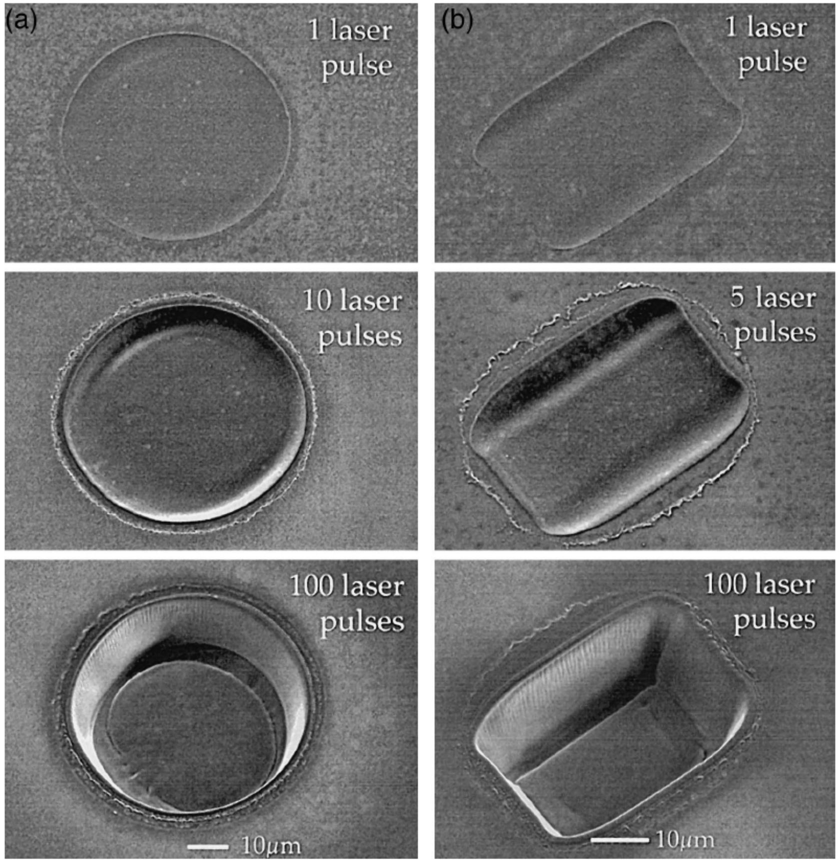

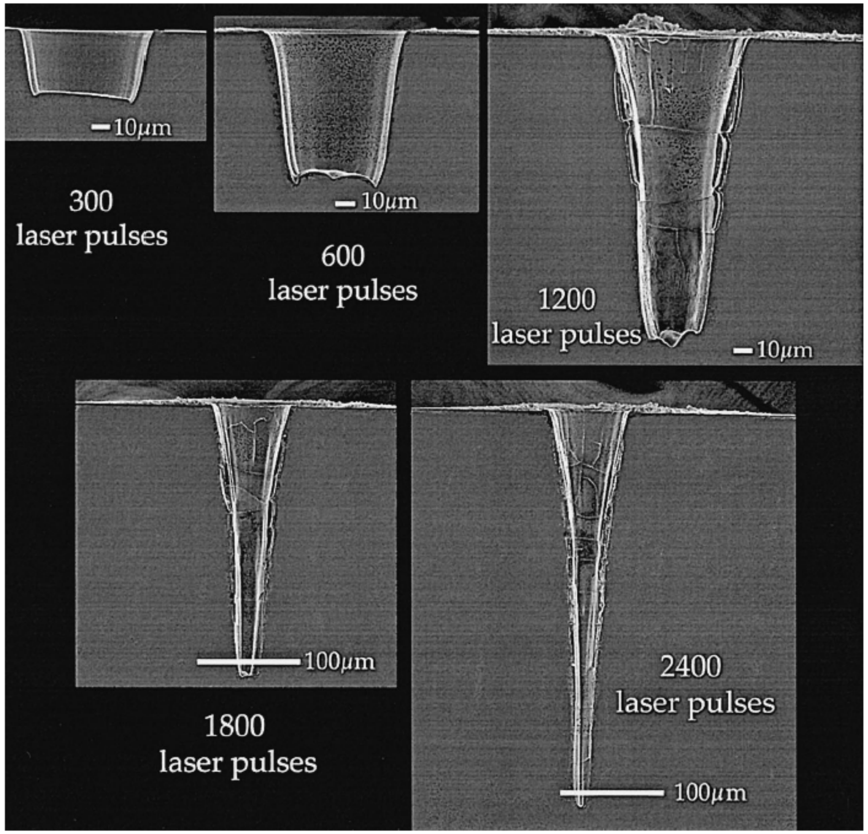

Bump formation

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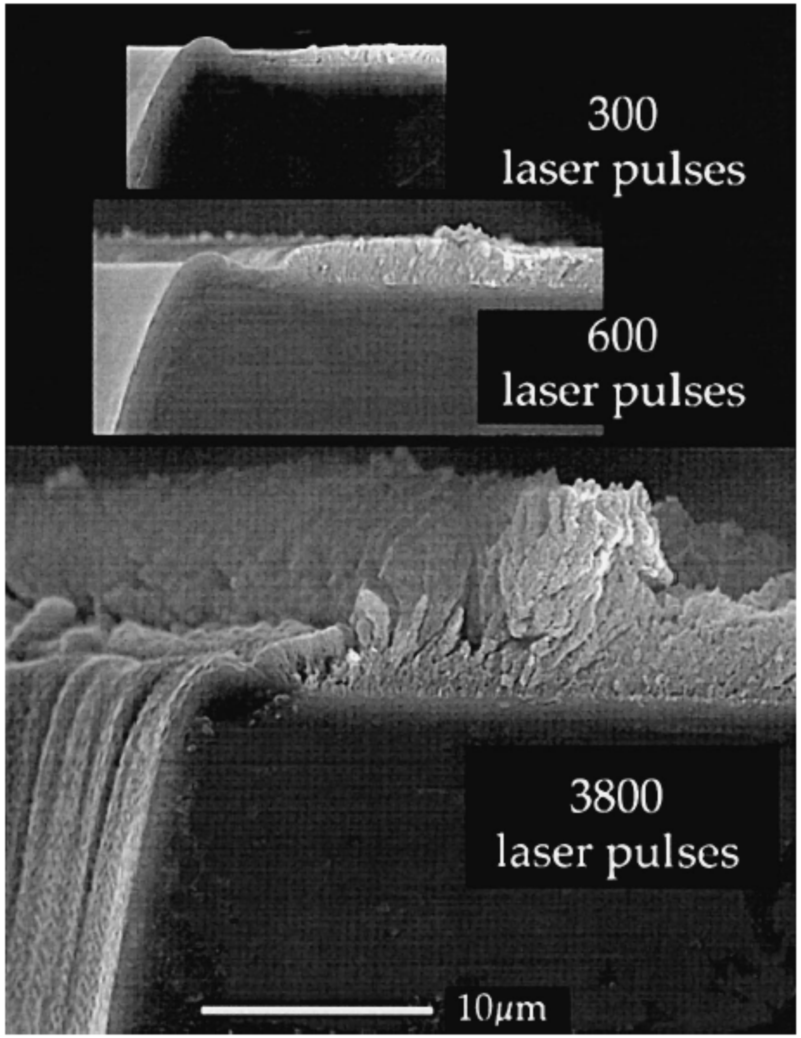

Damage processes vs. time and irradiance

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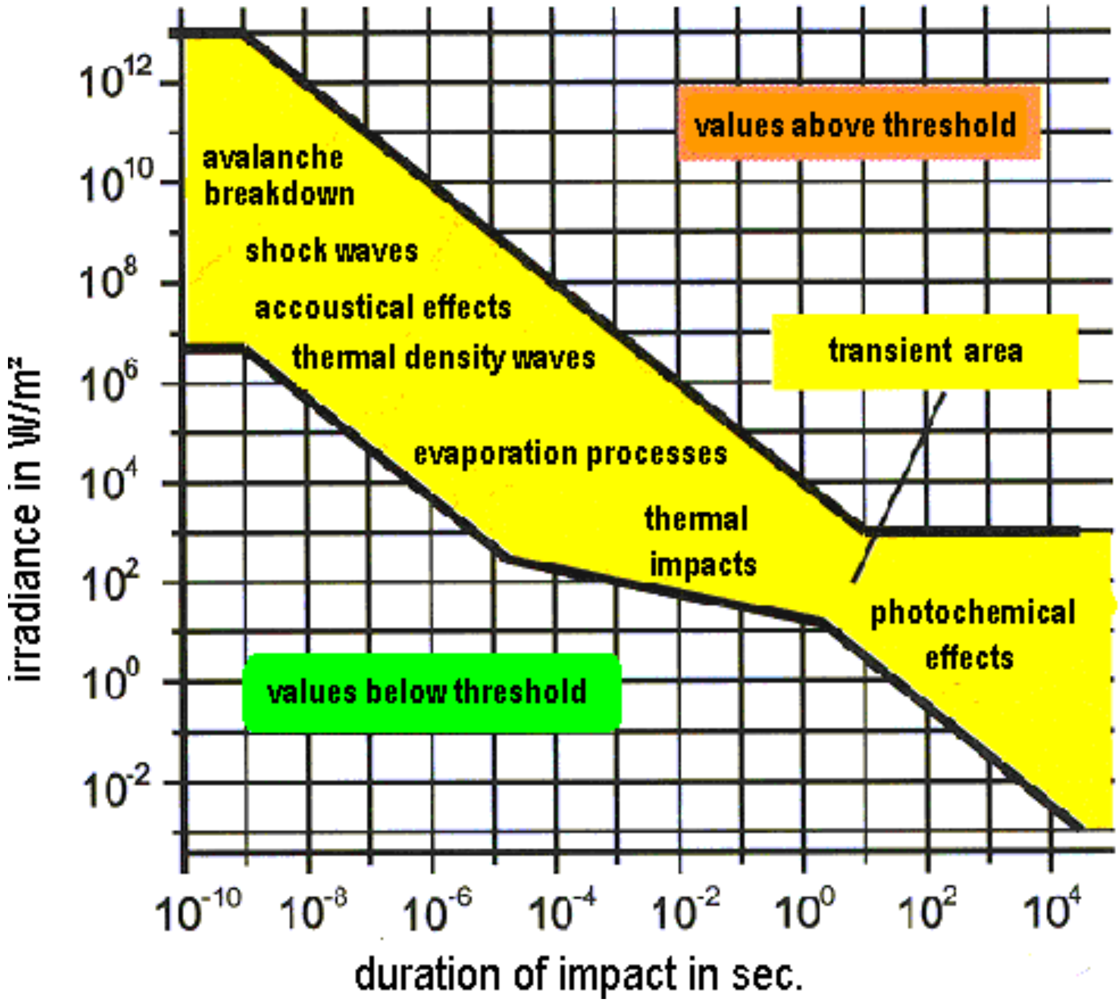

Experimental setup for laser machining

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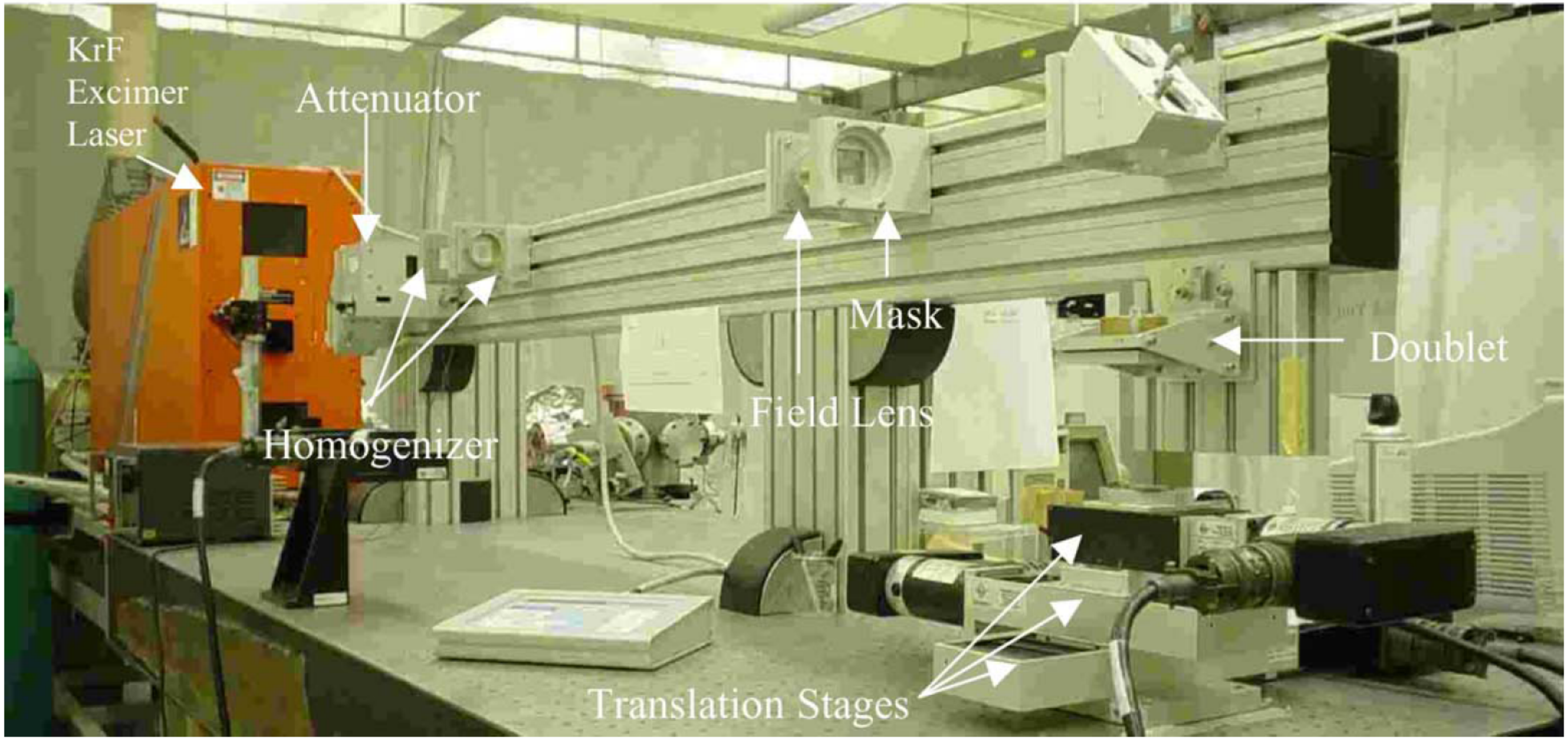

K. L. Choo et al., Mater. Sci. Eng. A 372, 145 (2004).

Laser machining for optical applications

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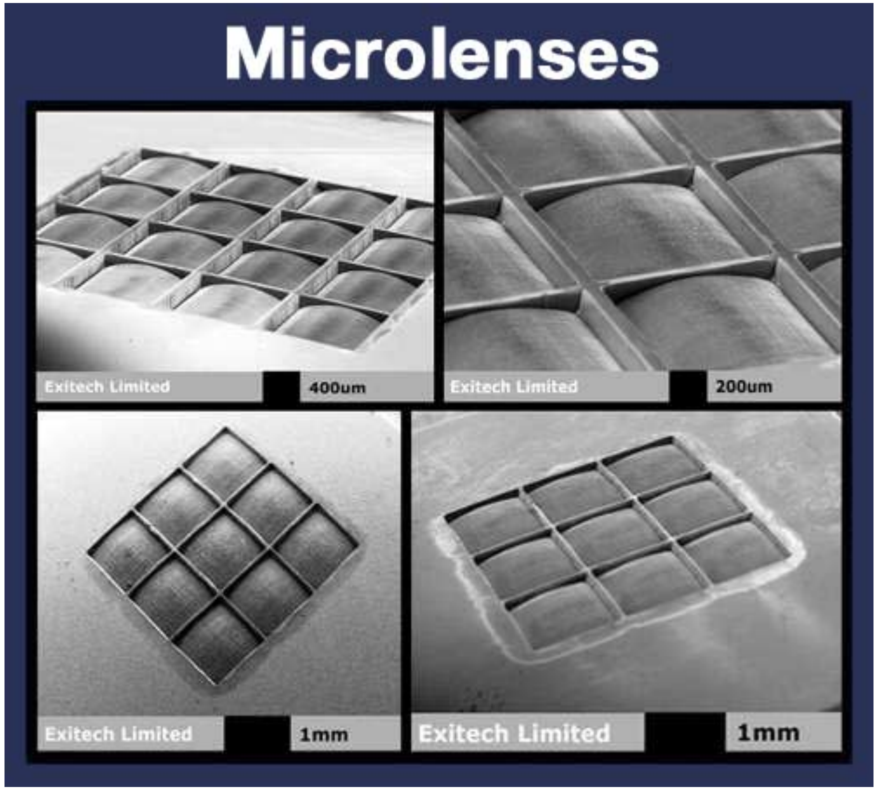

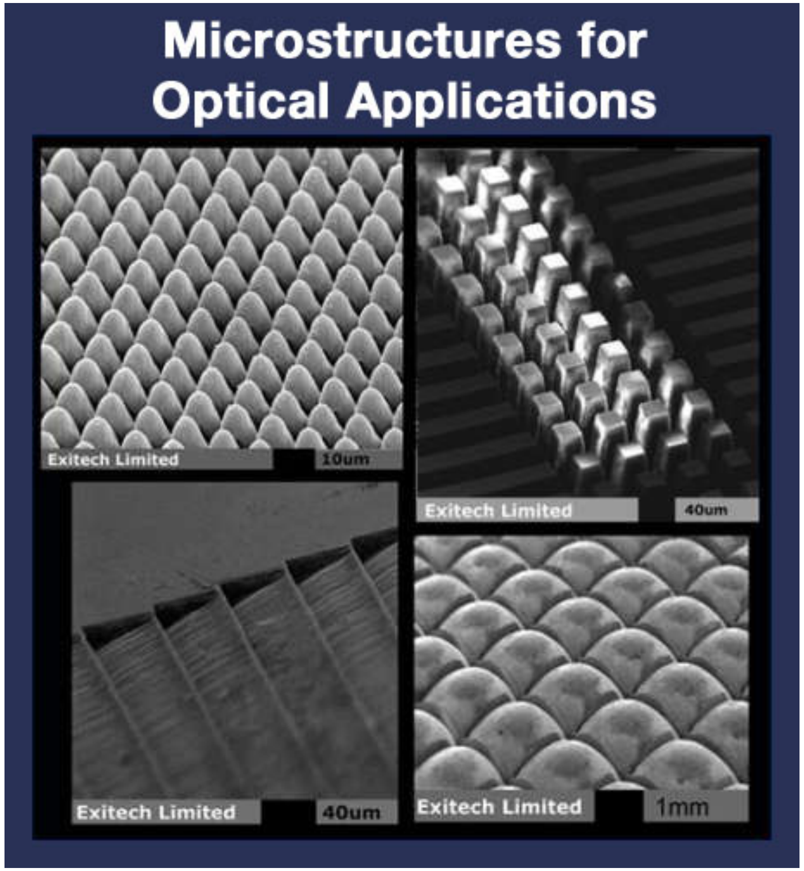

Laser machining for industry

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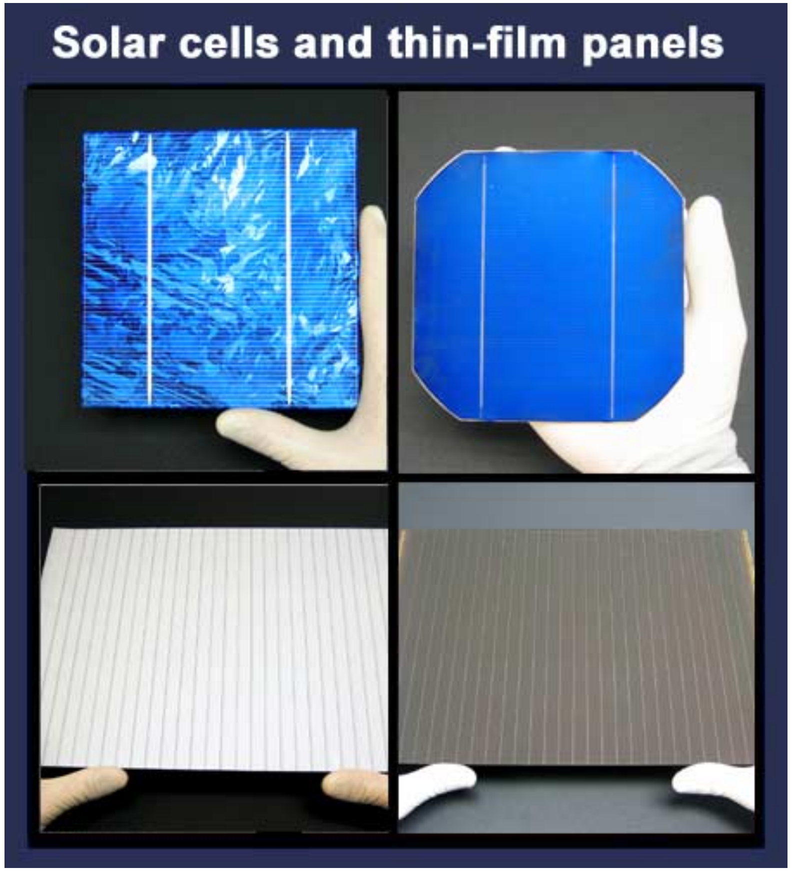

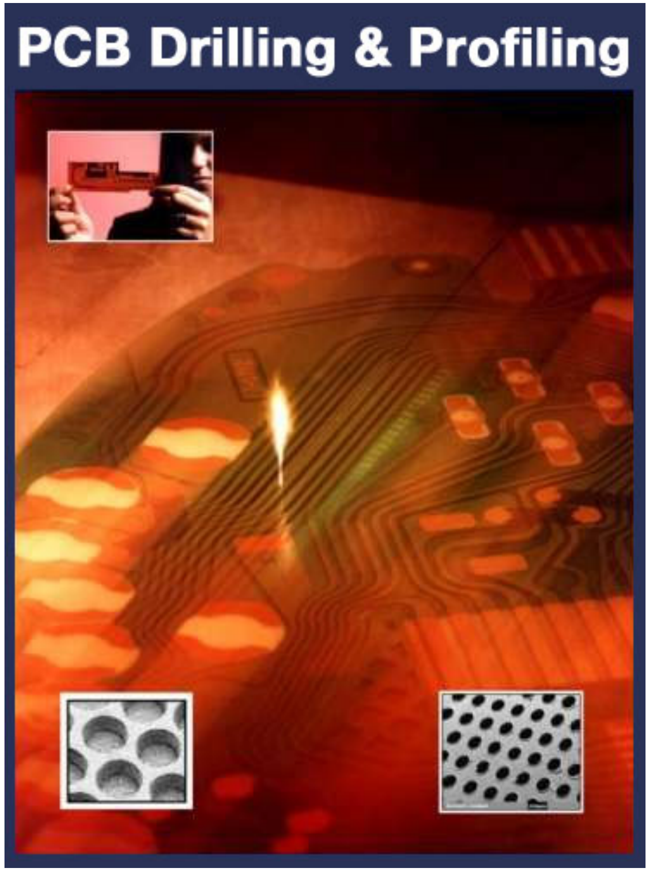

Laser machining for biochips

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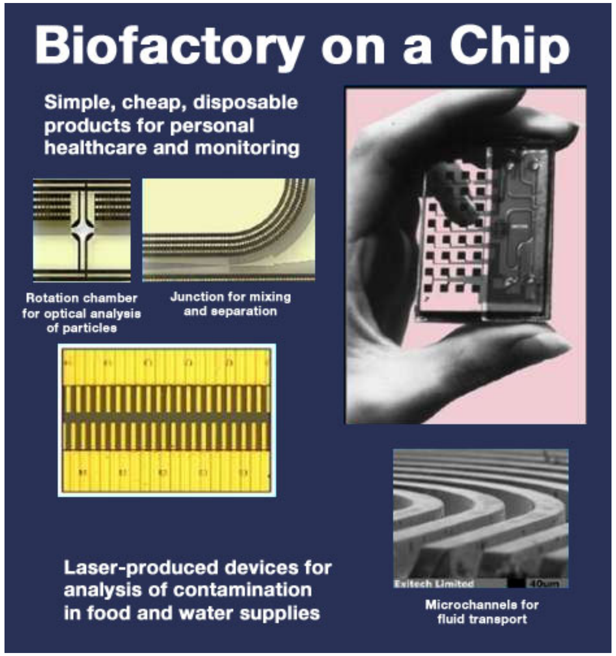

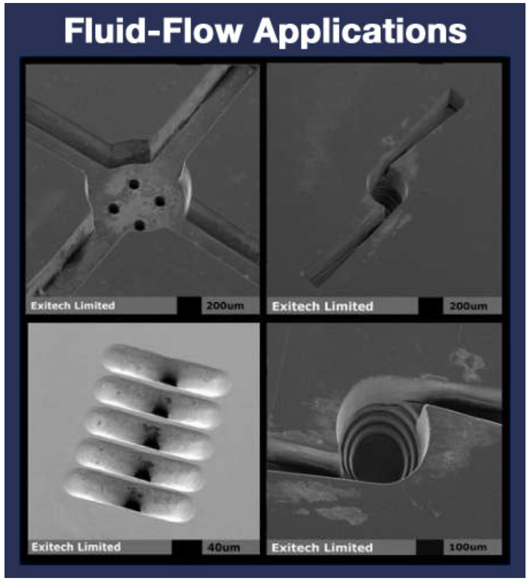

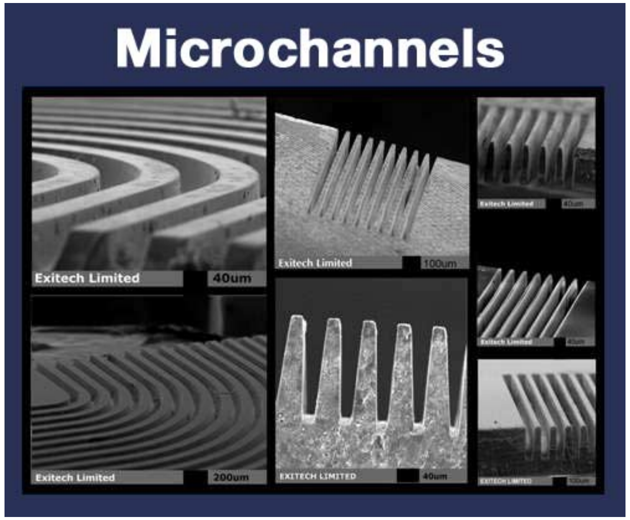

Laser machining of different materials

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