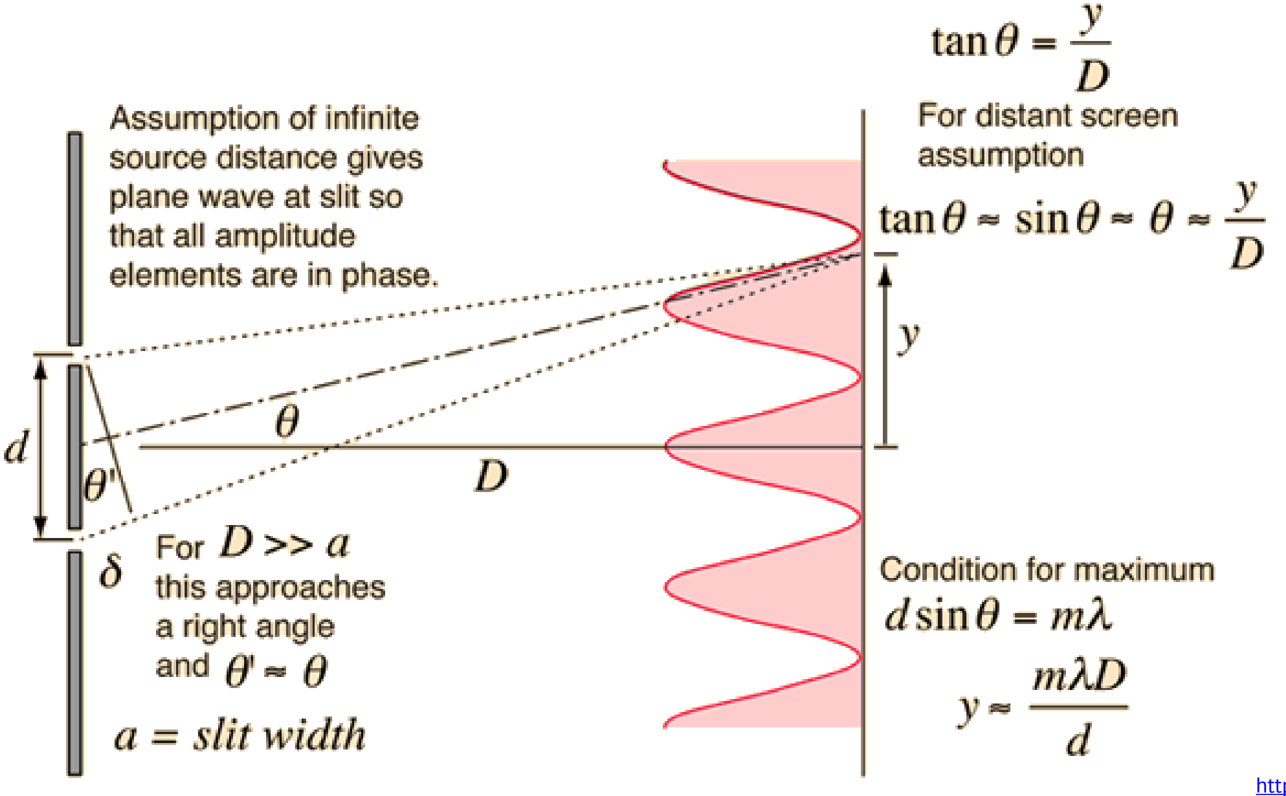
Interference

The wave properties of light lead to interference, but certain conditions of coherence must be met for these interference effects to be readily visible.

Double Slit Interference



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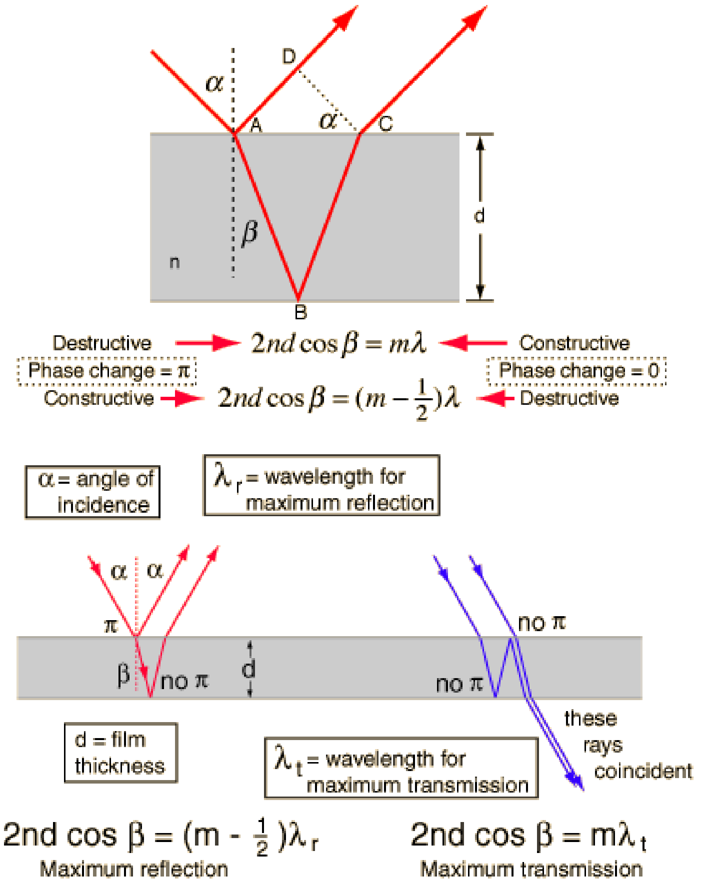
Thin Films

The optical properties of thin films arise from interference and reflection. The basic conditions for interference depend upon whether the reflections involve 180 degree phase changes.

Interference Condition for Thin Films



Optical pathlength difference Γ:

$$\Gamma = n(AB + BC) - AD$$

$$AB = \frac{d}{\cos\beta},\ AD = (2d\tan\beta)\sin\alpha,\ AD = 2d\tan\beta\,(n\sin\beta)$$

Collecting terms:

$$\Gamma = 2nd\left[\frac{1}{\cos\beta} - \tan\beta\sin\beta\right]$$

$$\Gamma = 2nd\left[\frac{1-\sin^2\beta}{\cos\beta}\right] = 2nd\cos\beta$$

Reflected light will experience a 180 degree phase change when it reflects from a medium of higher index of refraction and no phase change when it reflects from a medium of smaller index.

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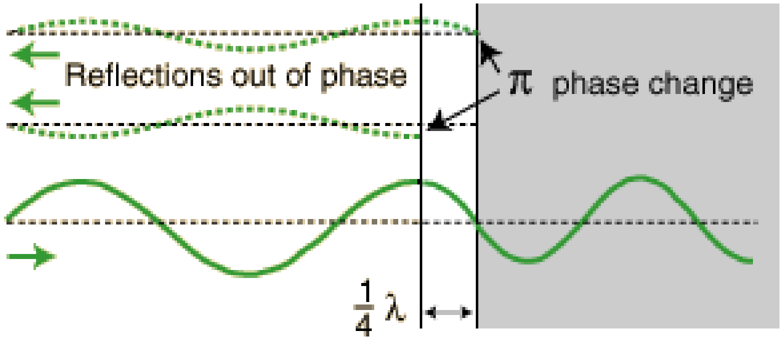
Anti-Reflection Coatings

Thin film anti-reflection coatings greatly reduce the light loss in multi-element lenses by making use of phase changes and the dependence of the reflectivity on index of refraction. A single quarter-wavelength coating of optimum index can eliminate reflection at one wavelength. Multi-layer coatings can reduce the loss over the visible spectrum.

The idea behind anti-reflection coatings is that the creation of a double interface by means of a thin film gives you two reflected waves. If these waves are out of phase, they partially or totally cancel. If the coating is a quarter wavelength thickness and the coating has an index of refraction less that the glass it is coating then the two reflections are 180 degrees out of phase.

Anti-reflection coatings work by producing two reflections which interfere destructively with each other.



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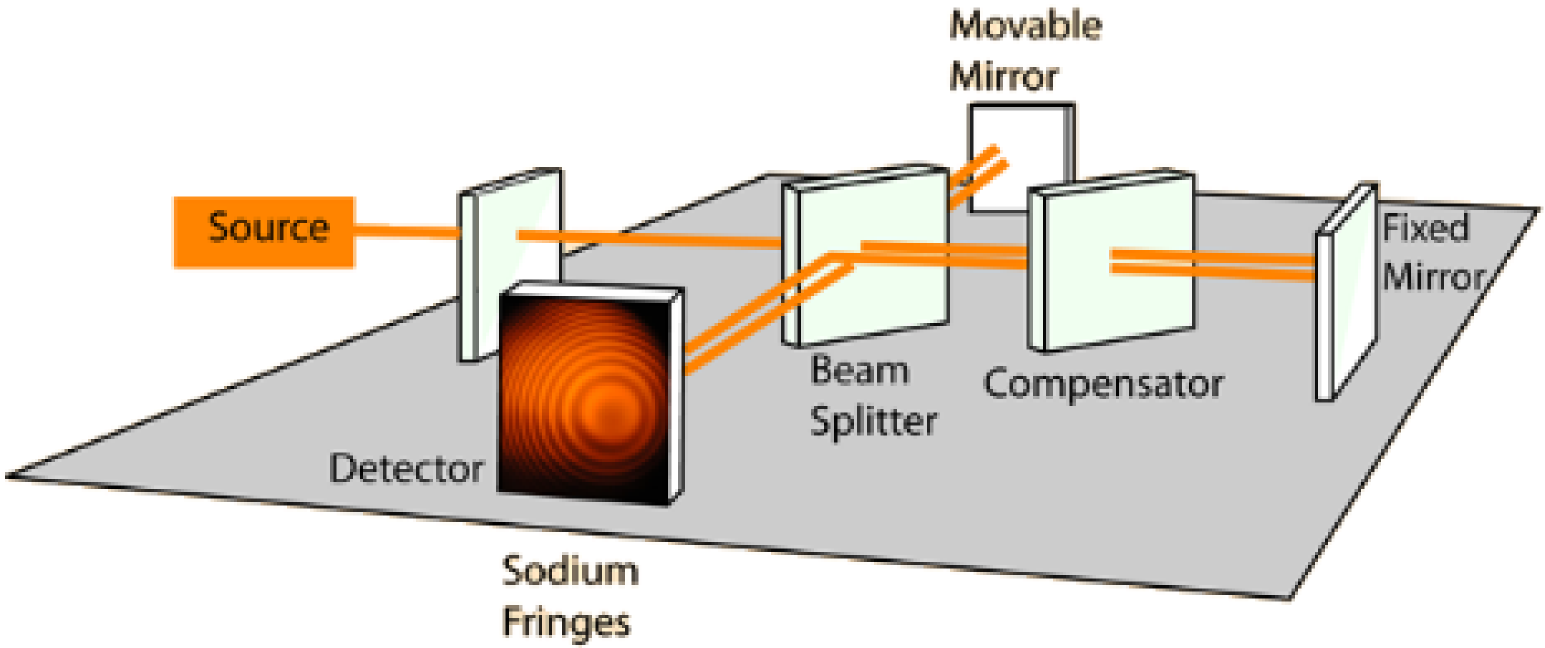
Michelson Interferometer

The Michelson interferometer produces interference fringes by splitting a beam of monochromatic light so that one beam strikes a fixed mirror and the other a movable mirror. When the reflected beams are brought back together, an interference pattern results.



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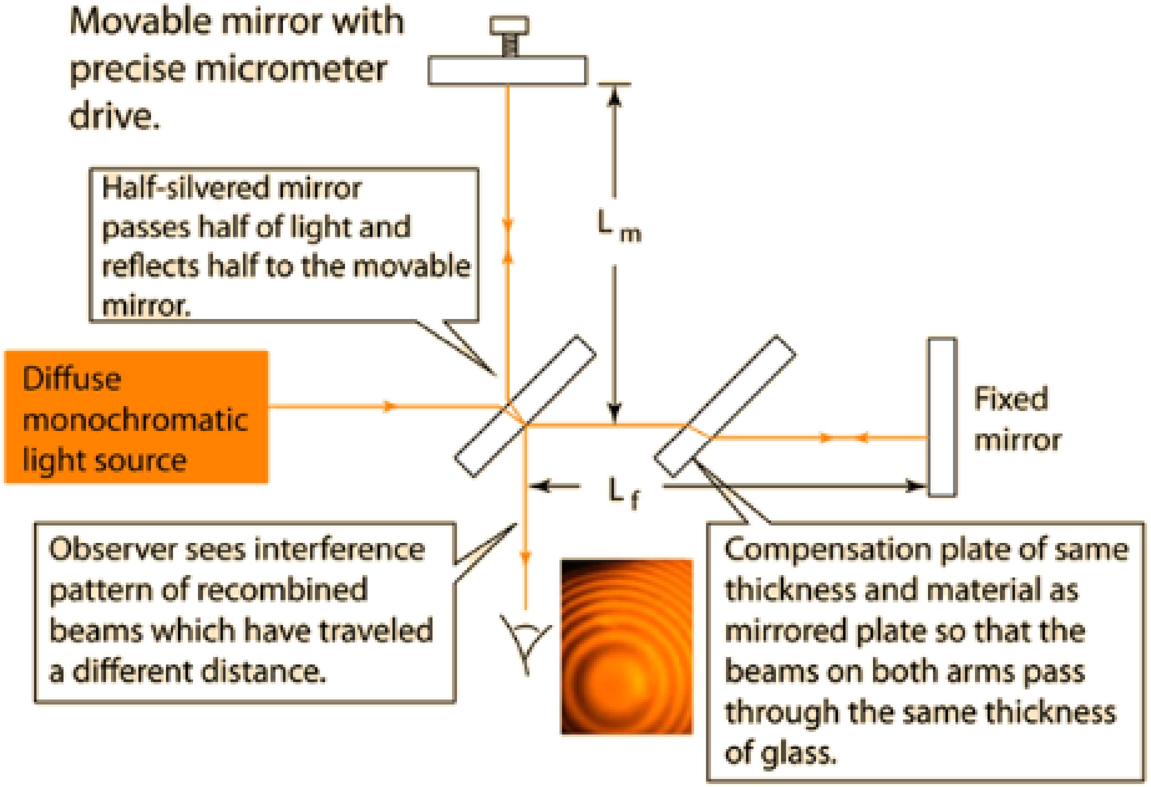
Michelson Interferometer

Precise distance measurements can be made with the Michelson interferometer by moving the mirror and counting the interference fringes which move by a reference point.

The distance ***d*** associated with ***m*** fringes is $d = m\lambda/2$



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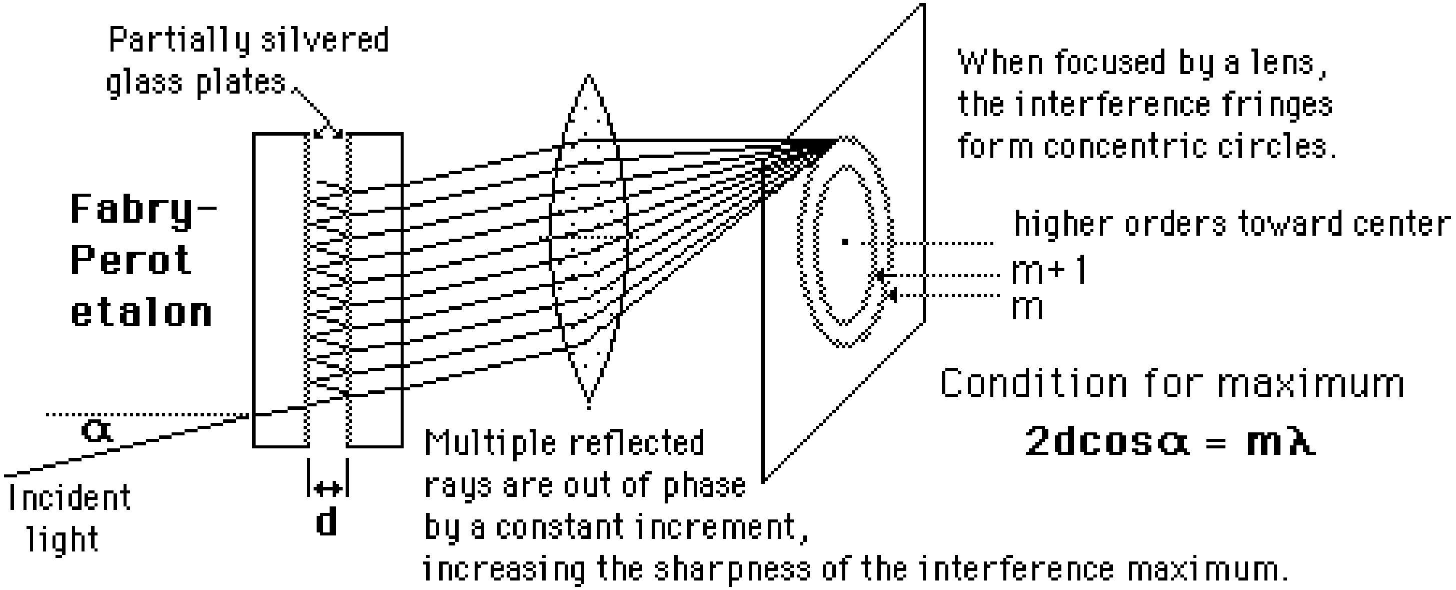
Lecture 8. Optics

Fabry-Perot Interferometer

This interferometer makes use of multiple reflections between two closely spaced partially silvered surfaces. Part of the light is transmitted each time the light reaches the second surface, resulting in multiple offset beams which can interfere with each other. The large number of interfering rays produces an interferometer with extremely high resolution, somewhat like the multiple slits of a diffraction grating increase its resolution.



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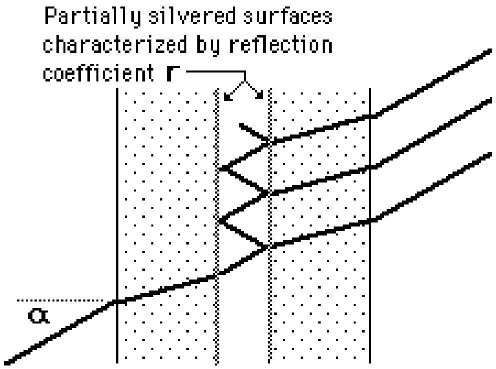
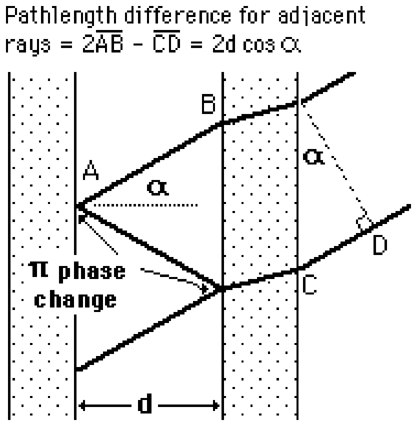
Fabry-Perot Interferometer





The Fabry-Perot Interferometer makes use of multiple reflections which follow the interference condition for thin films. The net phase change is zero for two adjacent rays, so the condition **2dcosα = mλ** represents an intensity maximum.

A high-resolution interferometer, the Fabry-Perot Interferometer has a resolvance of

$$\frac{\lambda}{\Delta\lambda} = \frac{m\pi\sqrt{r}}{1-r}$$

$$m = order\ of\ interference \approx \frac{2d}{\lambda}\ for\ small\ angles, r = reflectance\ of\ etalon\ surfaces$$

which means that the least separation of two spectral lines is given by

$$\Delta\lambda = \frac{\lambda(1-r)}{m\pi\sqrt{r}}$$

This separation means that the two wavelengths satisfy the Rayleigh criterion. The interferometer can also be characterized by its free spectral range, the change in wavelength necessary to shift the fringe system by one fringe:

$$\delta\lambda = \frac{\lambda^2}{2d}$$

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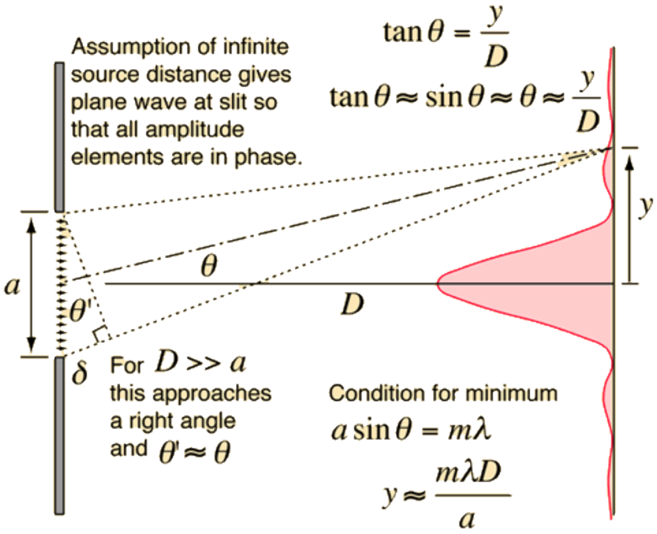
Diffraction

Diffraction manifests itself in the apparent bending of waves around small obstacles and the spreading out of waves past small openings.

Fraunhofer Diffraction

Fraunhofer diffraction deals with the limiting cases where the light appoaching the diffracting object is parallel and monochromatic, and where the image plane is at a distance large compared to the size of the diffracting object. The more general case where these restrictions are relaxed is called Fresnel diffraction.



Assumption of infinite source distance gives plane wave at slit so that all amplitude elements are in phase.

$$\tan\theta = \frac{y}{D}$$

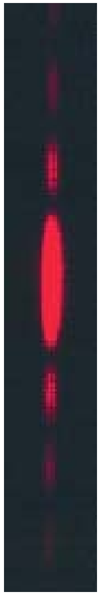
$$\tan\theta \approx \sin\theta \approx \theta \approx \frac{y}{D}$$

For $D >> a$ this approaches a right angle and $\theta' \approx \theta$

Condition for minimum

$$a\sin\theta = m\lambda$$

$$y \approx \frac{m\lambda D}{a}$$



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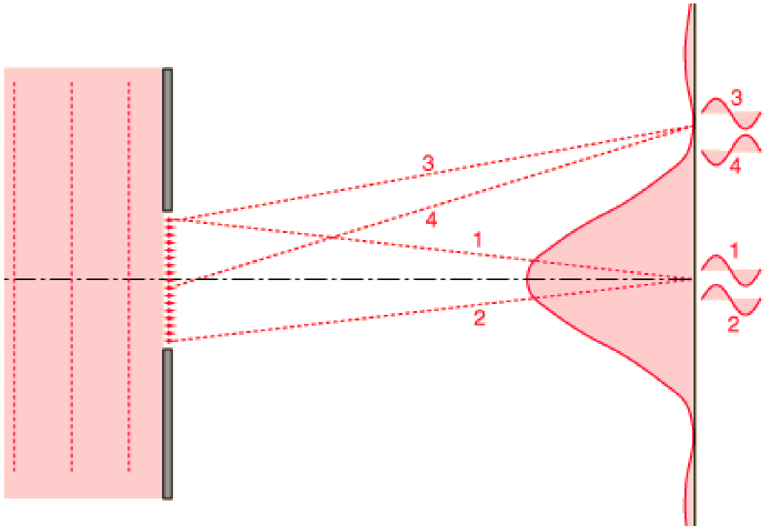
Fraunhofer Single Slit

The phenomenon of diffraction involves the spreading out of waves past openings which are on the order of the wavelength of the wave. The spreading of the waves into the area of the geometrical shadow can be modeled by considering small elements of the wavefront in the slit and treating them like point sources.



If light from symmetric elements near each edge of the slit travels to the centerline of the slit, as indicated by rays 1 and 2 above, their light arrives in phase and experiences constructive interference. Light from other element pairs symmetric to the centerline also arrive in phase. Although there is a progressive change in phase as you choose element pairs closer to the centerline, this center position is nevertheless the most favorable location for constructive interference of light from the entire slit and has the highest light intensity.

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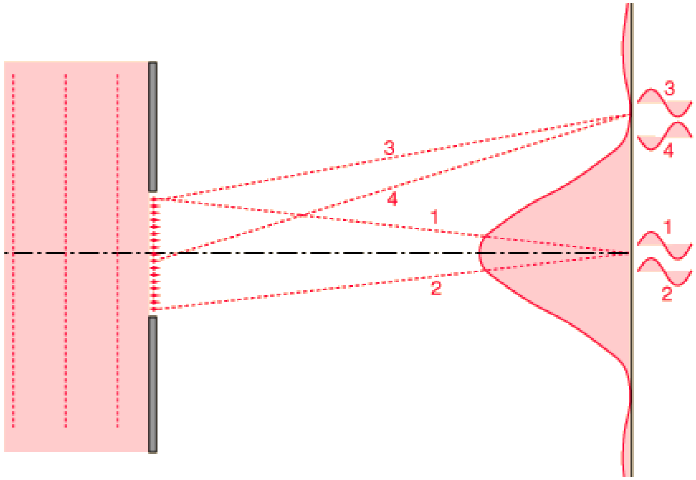
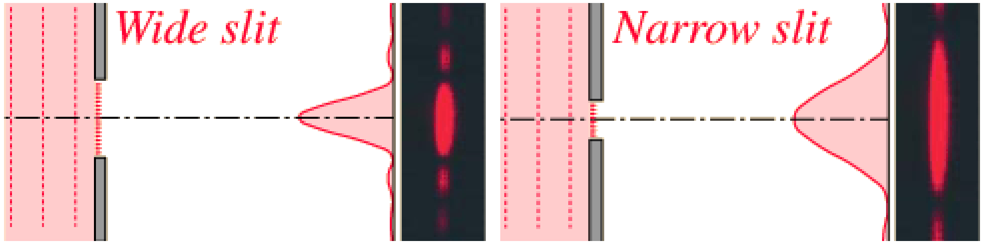
Fraunhofer Single Slit

The first minimum in intensity for the light through a single slit can be visualized in terms of rays 3 and 4. An element at one edge of the slit and one just past the centerline are chosen, and the condition for minimum light intensity is that light from these two elements arrive 180° out of phase, or a half wavelength different in pathlength. If those two elements suffer destructive interference, then choosing additional pairs of identical spacing which progress downward across the slit will give destructive interference for all those pairs and therefore an overall minimum in light intensity.





One of the characteristics of single slit diffraction is that a narrower slit will give a wider diffraction pattern, which seems somewhat counter-intuitive. One way to visualize it is to consider that rays 3 and 4 must reach one half wavelength difference in light pathlength, and if the slit is narrower, it will take a greater angle of the rays to achieve that difference.

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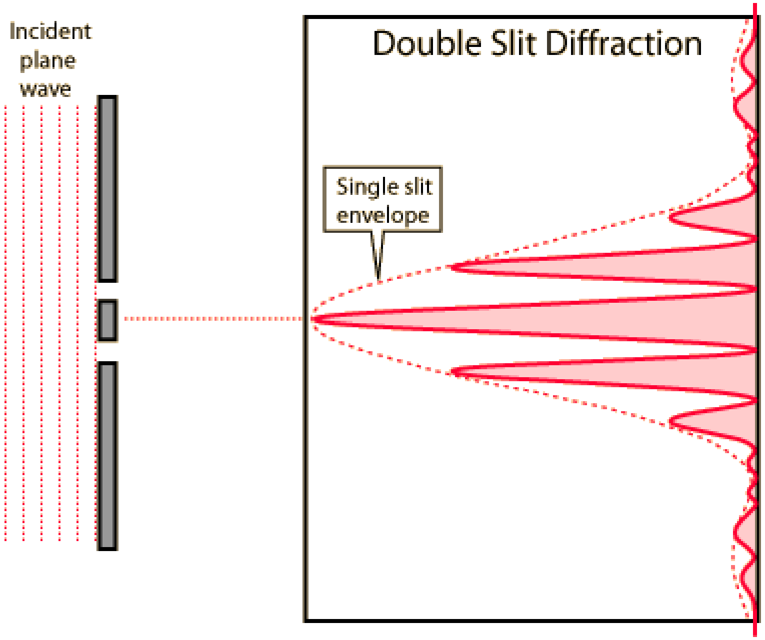
Double Slit Diffraction

The pattern formed by the interference and diffraction of coherent light is distinctly different for a single and double slit. The single slit intensity envelope is shown by the dashed line and that of the double slit for a particular wavelength and slit width is shown by the solid line. The photographs of the single and double slit patterns produced by a helium-neon laser show the qualitative differences between the patterns produced. You can see that the drawing is not to the same scale as the photographs, but the breaking up of the broad maxima of the single slit pattern into more closely spaced maxima is evident. The number of bright maxima within the central maximum of the single-slit pattern is influenced by the width of the slit and the separation of the double slits.



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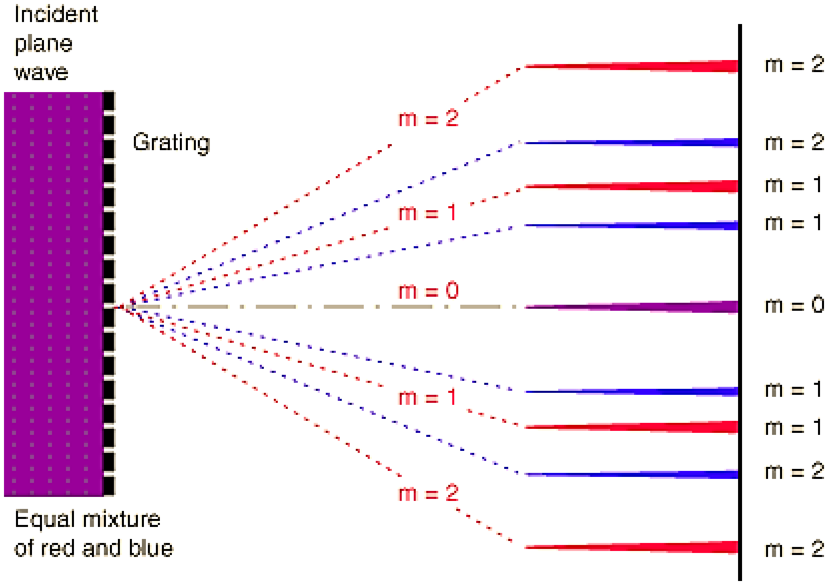
Diffraction Grating

When there is a need to separate light of different wavelengths with high resolution, then a diffraction grating is most often the tool of choice. This "super prism" aspect of the diffraction grating leads to application for measuring atomic spectra in both laboratory instruments and telescopes. A large number of parallel, closely spaced slits constitutes a diffraction grating. The condition for maximum intensity is the same as that for the double slit or multiple slits, but with a large number of slits the intensity maximum is very sharp and narrow, providing the high resolution for spectroscopic applications. The peak intensities are also much higher for the grating than for the double slit.



When light of a single wavelength , like the 632.8nm red light from a helium-neon laser at left, strikes a diffraction grating it is diffracted to each side in multiple orders. Orders 1 and 2 are shown to each side of the direct beam. Different wavelengths are diffracted at different angles, according to the grating relationship.

The condition for maximum intensity is the same as that for a double slit. However, angular separation of the maxima is generally much greater because the slit spacing is so small for a diffraction grating.

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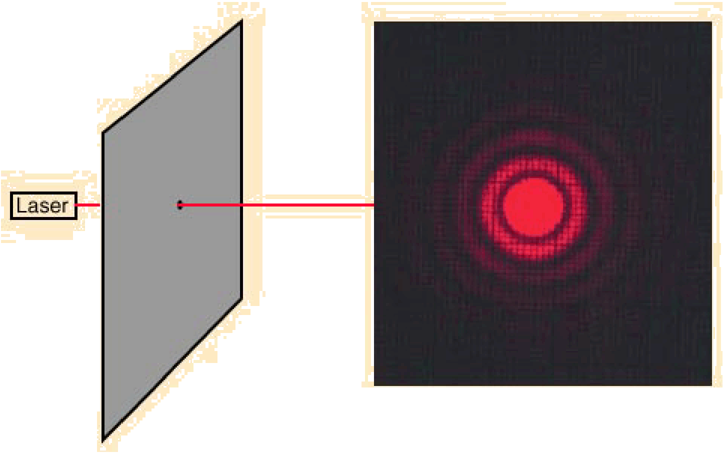
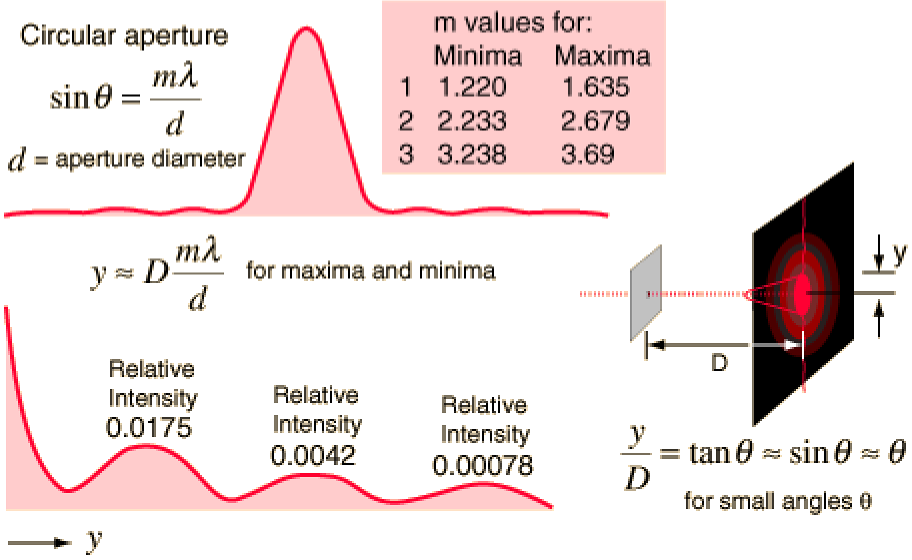
Circular Aperture Diffraction

When light from a point source passes through a small circular aperture, it does not produce a bright dot as an image, but rather a diffuse circular disc known as Airy's disc surrounded by much fainter concentric circular rings.

This example of diffraction is of great importance because the eye and many optical instruments have circular apertures. If this smearing of the image of the point source is larger that that produced by the aberrations of the system, the imaging process is said to be diffraction-limited, and that is the best that can be done with that size aperture. This limitation on the resolution of images is quantified in terms of the Rayleigh criterion so that the limiting resolution of a system can be calculated.





Circular aperture

$$\sin\theta = \frac{m\lambda}{d}$$

d = aperture diameter

m values for:	Minima	Maxima
1	1.220	1.635
2	2.233	2.679
3	3.238	3.69

$$y \approx D\frac{m\lambda}{d}$$ for maxima and minima

$$\frac{y}{D} = \tan\theta \approx \sin\theta \approx \theta$$

for small angles θ

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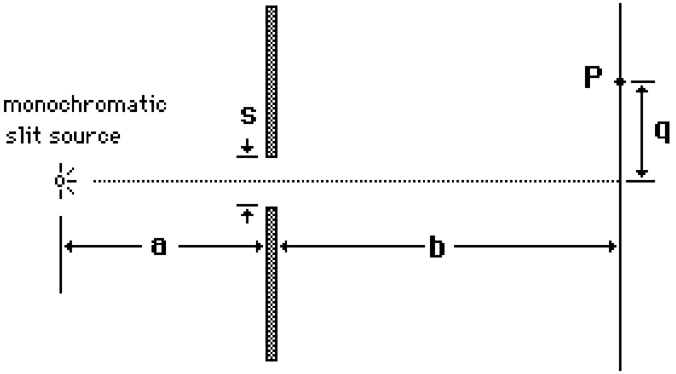
Fresnel Diffraction

Fraunhofer diffraction is the special case where the incoming light is assumed to be parallel and the image plane is assumed to be at a very large distance compared to the diffracting object. Fresnel diffraction refers to the general case where those restrictions are relaxed. This makes it much more complex mathematically. Some cases can be treated in a reasonable empirical and graphical manner to explain some observed phenomena.

The more accurate Fresnel treatment of the single slit gives a pattern which is similar in appearance to that of the Fraunhofer single slit except that the minima are not exactly zero.

For the Fresnel case, all length parameters are allowed to take comparable values, so all must be included as variables in the problem. The usual geometry assumes a monochromatic slit source and the problem is set up in terms of a parameter v as defined below. This parameter is used with the Cornu spiral or a table of elliptical integrals.



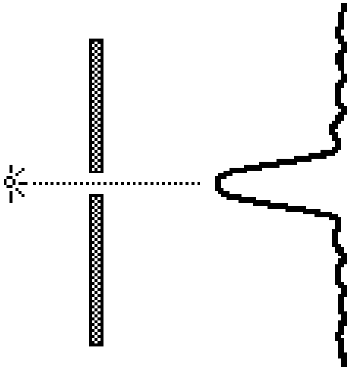
To calculate the intensity at point P, the geometry is set up in terms of the **parameter v** which is used with the **Cornu spiral**.

$$v = v_1 - v_2$$

$$v_1 = \left[\frac{s}{2} + k\right]\sqrt{\frac{2(a+b)}{ab\lambda}}$$

$$v_2 = \left[\frac{-s}{2} + k\right]\sqrt{\frac{2(a+b)}{ab\lambda}}$$

where $k = q\left[\frac{a}{a+b}\right]$



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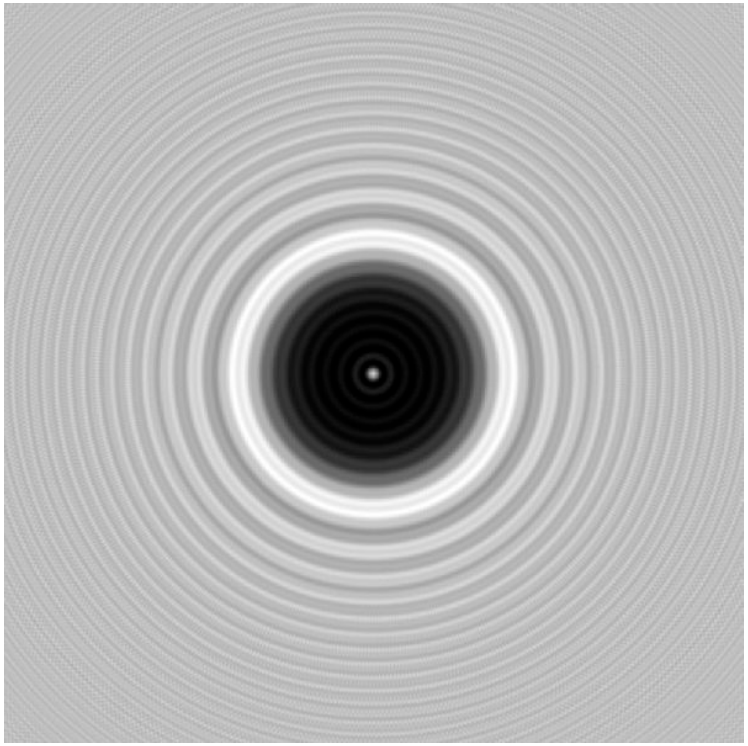
Fresnel Diffraction



An opaque circular disk gives a concentric ring diffraction pattern similar to the circular aperture, but in addition it has a bright spot in the center referred to as either Poisson's spot or Fresnel's spot. It seems more appropriate to name it after Fresnel since he developed the theory.

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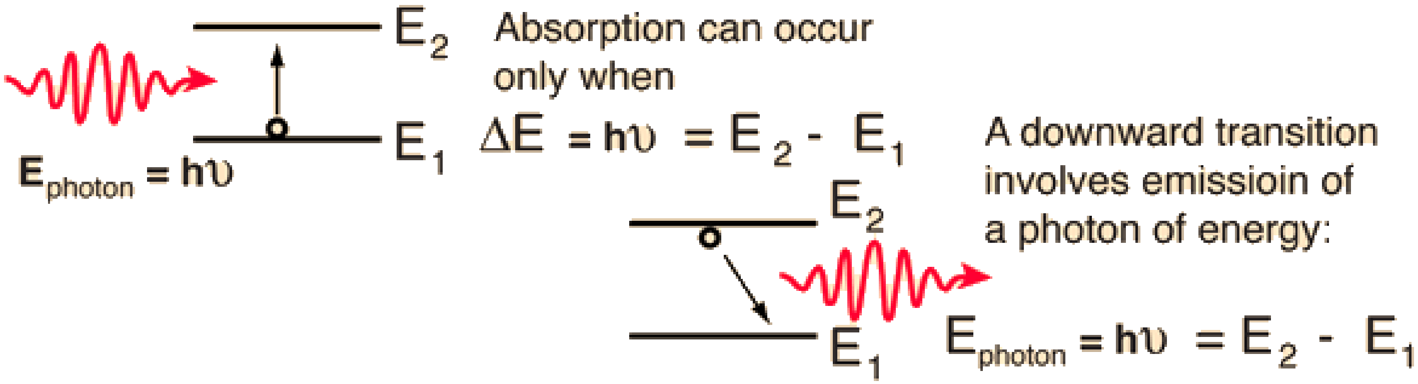
Quantum Properties of Light

Quantum processes dominate the fields of atomic and molecular physics. The treatment here is limited to a review of the characteristics of absorption, emission, and stimulated emission which are essential to an understanding of lasers and their applications.

Atomic transitions which emit or absorb visible light are generally electronic transitions, which can be pictured in terms of electron jumps between quantized atomic energy levels.



Note that the frequency that is emitted when an electron makes the downward transition is the same as the frequency absorbed by this two-level system. This can be generalized to the multiple energy levels of atoms. The emission spectra of atoms are the series of frequencies emitted by those atoms in gaseous form. If these same gases were cool, the same series of frequencies would be selectively absorbed.

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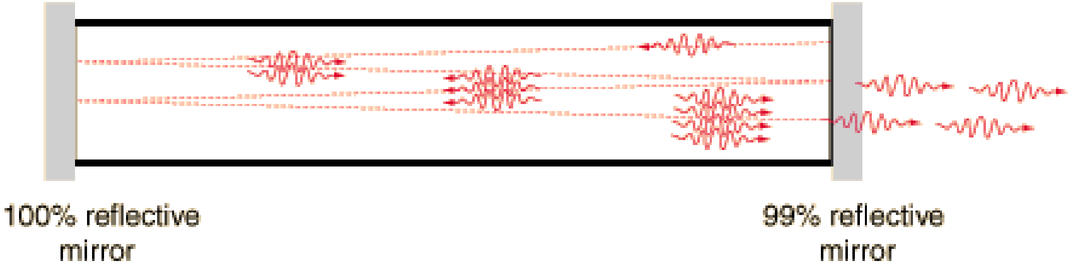
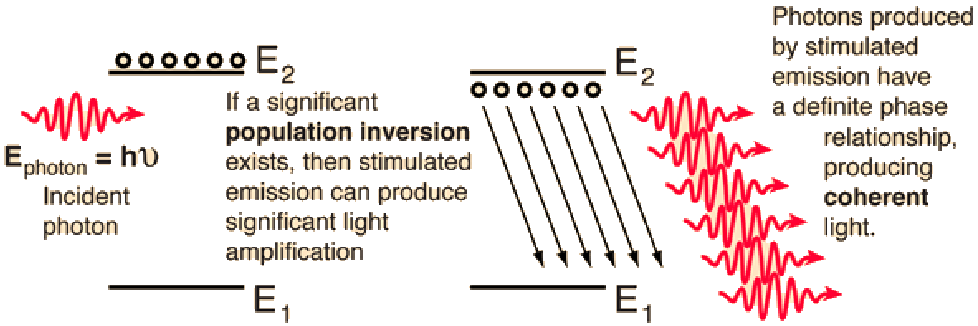
Lasers

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



The stimulated emission of light is the crucial quantum process necessary for the operation of a laser.

The light from a typical laser emerges in an extremely thin beam with very little divergence. Another way of saying this is that the beam is highly "collimated". An ordinary laboratory helium-neon laser can be swept around the room and the red spot on the back wall seems about the same size at that on a nearby wall.



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Characteristics of Laser Light

1. **Coherent.** Different parts of the laser beam are related to each other in phase. These phase relationships are maintained over long enough time so that interference effects may be seen or recorded photographically. This coherence property is what makes holograms possible.

2. **Monochromatic**. Laser light consists of essentially one wavelength, having its origin in stimulated emission from one set of atomic energy levels.

3. **Collimated.** Because of bouncing back between mirrored ends of a laser cavity, those paths which sustain amplification must pass between the mirrors many times and be very nearly perpendicular to the mirrors. As a result, laser beams are very narrow and do not spread very much.

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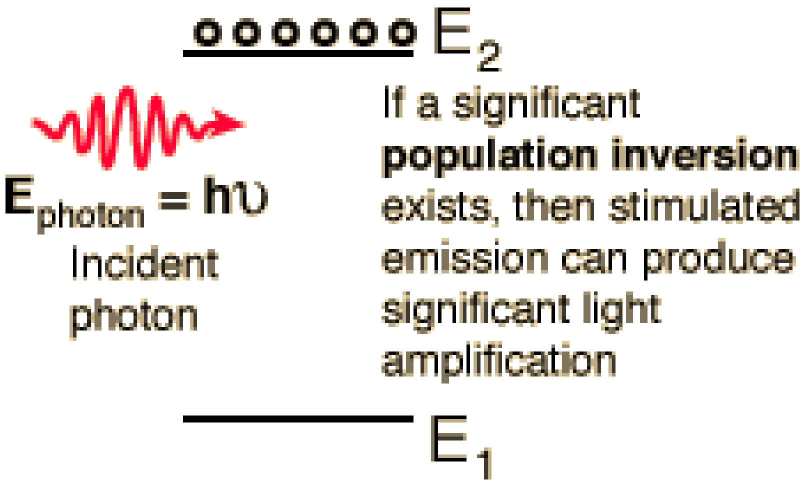
Population Inversion

The achievement of a significant population inversion in atomic or molecular energy states is a precondition for laser action. Electrons will normally reside in the lowest available energy state. They can be elevated to excited states by absorption, but no significant collection of electrons can be accumulated by absorption alone since both spontaneous emission and stimulated emission will bring them back down.

A population inversion cannot be achieved with just two levels because the probabability for absorption and for spontaneous emission is exactly the same, as shown by Einstein and expressed in the Einstein A and B coefficients. The lifetime of a typical excited state is about 10^{-8} seconds, so in practical terms, the electrons drop back down by photon emission about as fast as you can pump them up to the upper level. The case of the helium-neon laser illustrates one of the ways of achieving the necessary population inversion.



If a significant **population inversion** exists, then stimulated emission can produce significant light amplification

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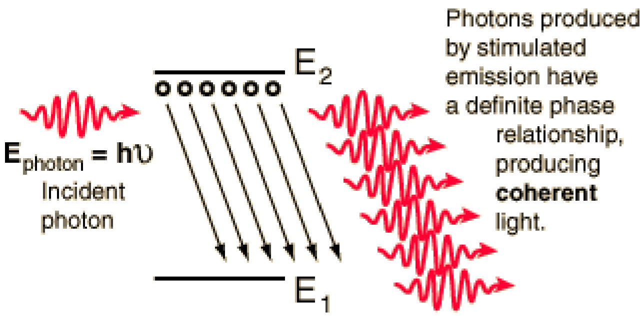
Coherent Light

Coherence is one of the unique properties of laser light. It arises from the stimulated emission process which provides the amplification. Since a common stimulus triggers the emission events which provide the amplified light, the emitted photons are "in step" and have a definite phase relation to each other. This coherence is described in terms of temporal coherence and spatial coherence, both of which are important in producing the interference which is used to produce holograms.



Photons produced by stimulated emission have a definite phase relationship, producing **coherent** light.

Ordinary light is not coherent because it comes from independent atoms which emit on time scales of about 10^{-8} seconds. There is a degree of coherence in sources like the mercury green line and some other useful spectral sources, but their coherence does not approach that of a laser

Monochromatic Laser Light

The light from a laser typically comes from one atomic transition with a single precise wavelength. So the laser light has a single spectral color and is almost the purest monochromatic light available.

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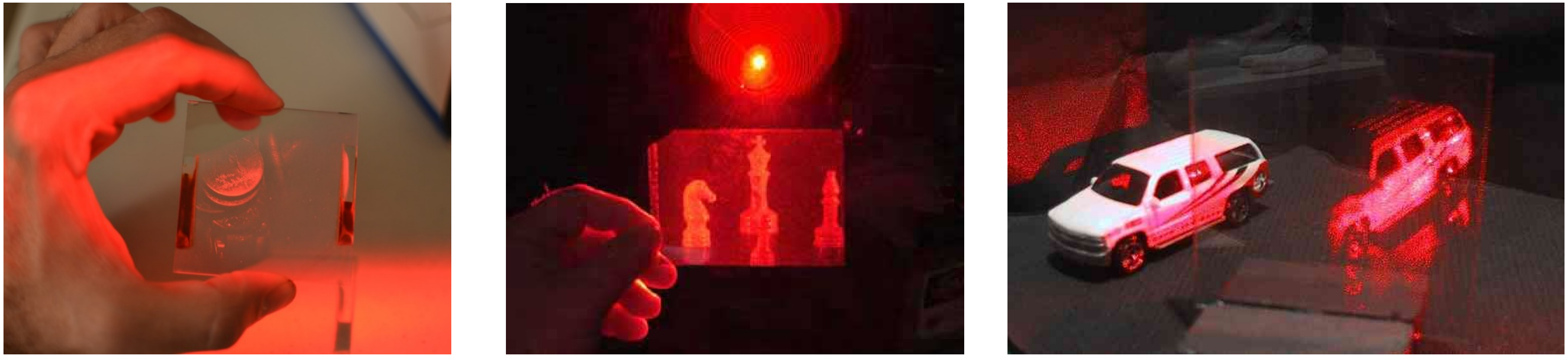
Holography



Holography is "lensless photography" in which an image is captured not as an image focused on film, but as an interference pattern at the film. Typically, coherent light from a laser is reflected from an object and combined at the film with light from a reference beam. This recorded interference pattern actually contains much more information that a focused image, and enables the viewer to view a true three-dimensional image which exhibits parallax. That is, the image will change its appearance if you look at it from a different angle, just as if you were looking at a real 3D object. In the case of a transmission hologram, you look through the film and see the three dimensional image suspended in midair at a point which corresponds to the position of the real object which was photographed.

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