III. Light is a Wave (Physical Optics)

III.D. Interferometers

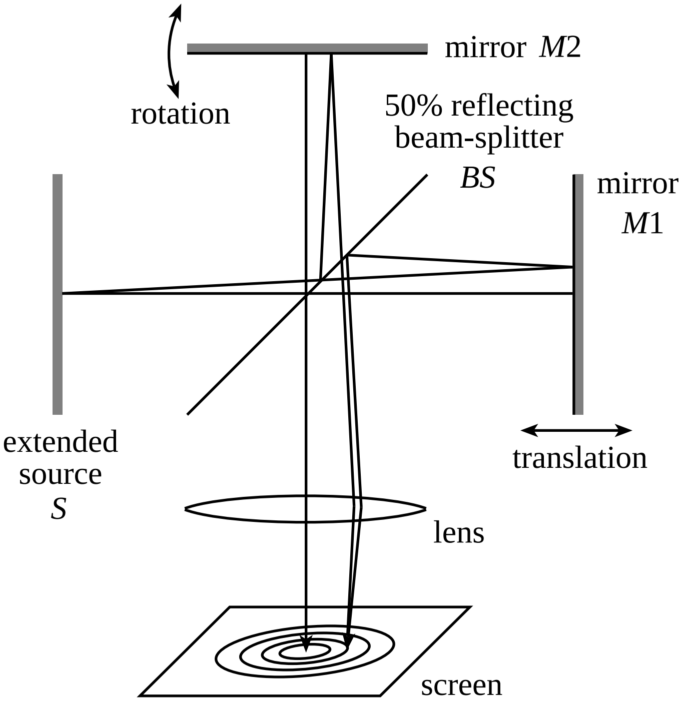
1. Michelson Interferometer

Optical interferometers are combinations of partially and fully reflecting mirrors, and sometimes lenses, that form an interference pattern. By analyzing the interference pattern, we can measure various properties of optical components that are placed within or are part of the interferometer, as well as properties of light waves themselves.

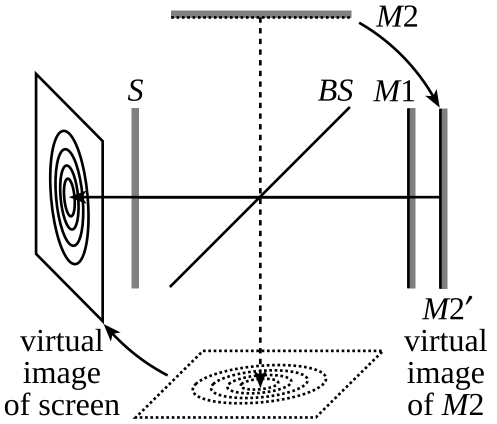
Perhaps the most well-known interferometer is the Michelson interferometer. This arrangement was introduced by Albert Michelson in 1881, and has proved to be a key instrument in modern science. Some of its claims to fame include:

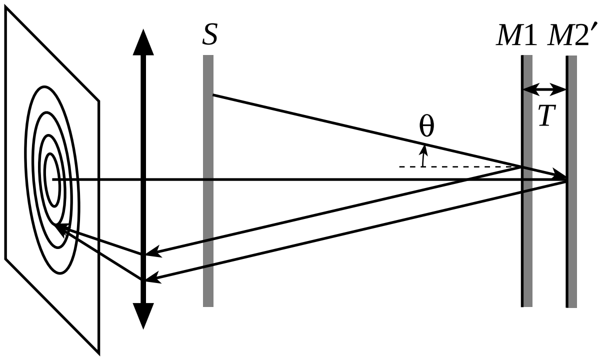
- provided experimental evidence for special relativity
- discovered hyperfine structure in the energy levels of atoms
- measured tidal effects of the moon on the earth
- enabled the use of wavelength of light as the international standard for the meter.

In its most common arrangement, a Michelson interferometer is illuminated by an extended source *S* (as opposed to a point source), and consists of a 50% beam-splitter *BS* and 2 mirrors *M*1 and *M*2. The interference pattern is observed on a screen that is either very far from *BS* or has a lens placed one focal length in front of it, and can be adjusted by rotating and/or translating the mirror(s).



Interference in a Michelson can be understood in terms of thin-film interference by “folding” the arms of the interferometer such that there is a single optical axis, as shown in the drawing below on the left. A close-up view of the folded interferometer (below right) reveals that reflection from the 2 mirrors is analogous to reflection from 2 surfaces of an thin air gap of thickness *T*.

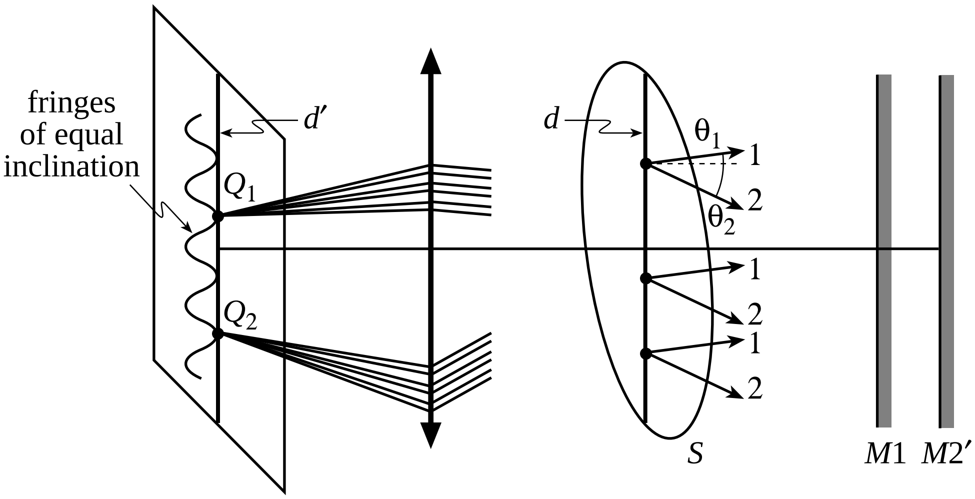




Thus, for example, we find

$$m\lambda_0 = 2T\cos\theta \quad \Rightarrow \quad \text{constructive interference}.$$

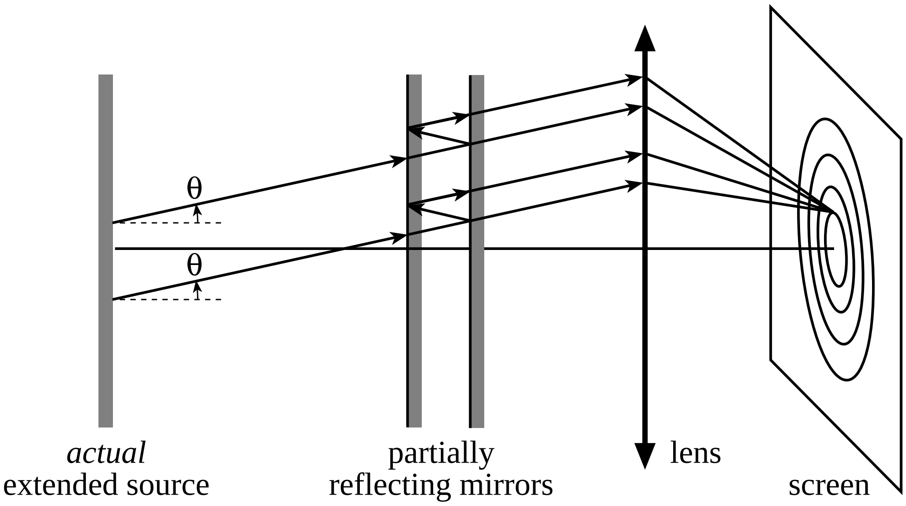
In a standard Michelson configuration, we observe circular fringes on the screen. Why? Looking at the drawing below, we see that along any given diameter line *d* on the source *S*, light that leaves from any point at an angle θ_i is imaged to a particular point Q_i on the screen, where points Q_i lie on a line d'. Because of the circular symmetry of the folded arrangement, rotating the line *d* causes the line d' and its associated radially dependent interference pattern to rotate also. Since the radial variation of the pattern doesn't change as we rotate these lines, we must get circular fringes.



Notice that the fringes are analogous to *fringes of equal inclination* that we obtain when we shine light from an extended source on a thin film.

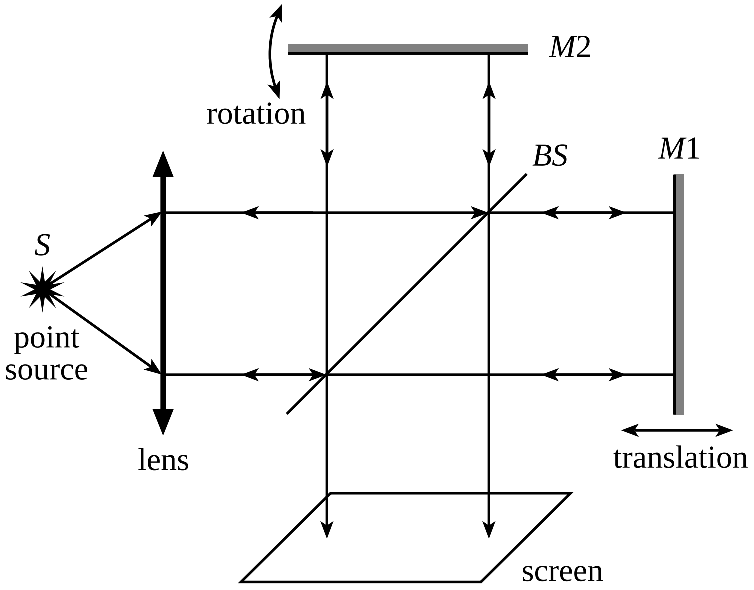
2. Fabry-Perot Etalon

This interferometer is simply an *actual* folded Michelson interferometer! The only difference is that in a Fabry-Perot etalon we observe the interference pattern formed by light that is transmitted through the two (partially reflecting) mirrors, rather than reflected as in the Michelson.



3. Twyman-Green Interferometer

This interferometer is a slightly different configuration of a Michelson interferometer in which collimated light from a point source is used instead of an extended source.



If mirrors $M1$ and $M2$ are perpendicular, and the beam-splitter BS is at a 45° angle relative to both mirrors, then the interference is exactly analogous to thin-film interference at normal incidence.

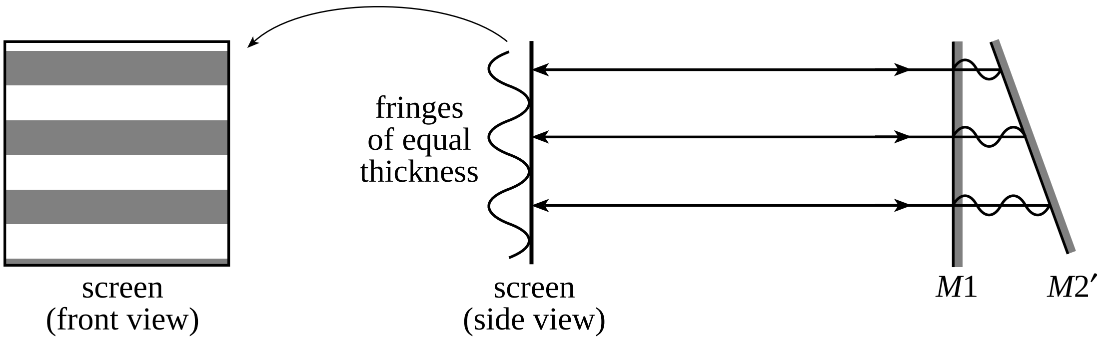
Thus we obtain complete constructive interference such that all of the light from the source reaches the screen when

$$T = m\lambda_0/2 \quad \Rightarrow \quad \text{constructive interference},$$

where T is the path length difference between the 2 arms adjusted by translating, say, $M1$. We get complete destructive interference such that no light hits the screen (and thus all of the light reflects back to the source) when

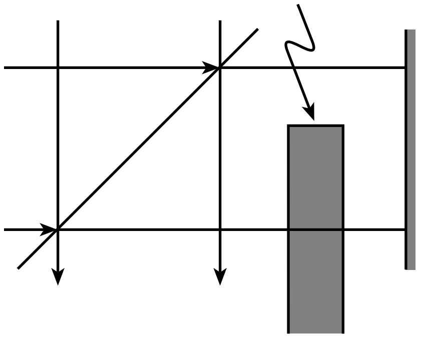
$$T = \left(m + \tfrac{1}{2}\right)\lambda_0/2 \quad \Rightarrow \quad \text{destructive interference}.$$

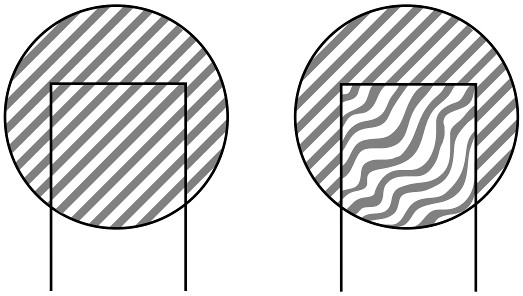
If we rotate one of the mirrors (say $M2$), then we see *fringes of equal thickness* on the screen, since the angle of incidence is constant. That is, this situation is exactly analogous to interference of collimated light in a thin film with varying thickness.



Twyman-Green interferometers are particularly useful for testing optical components, like lenses, curved and flat mirrors, beam-splitters, prisms, and flats. Often one of the mirrors is intentionally tilted to create fringes. The quality of the component can then be determined from the change in the fringe pattern when the component is placed in the interferometer.

Testing a flat

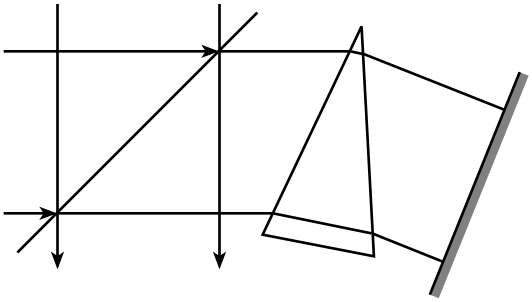




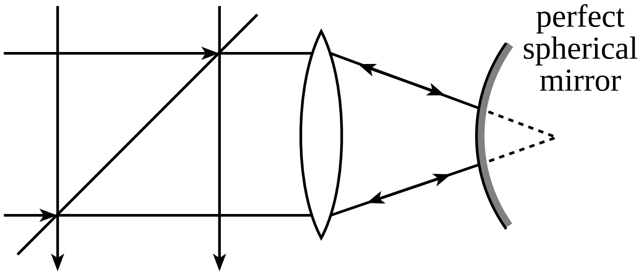
Perfect Flat

Imperfect Flat

Testing a prism



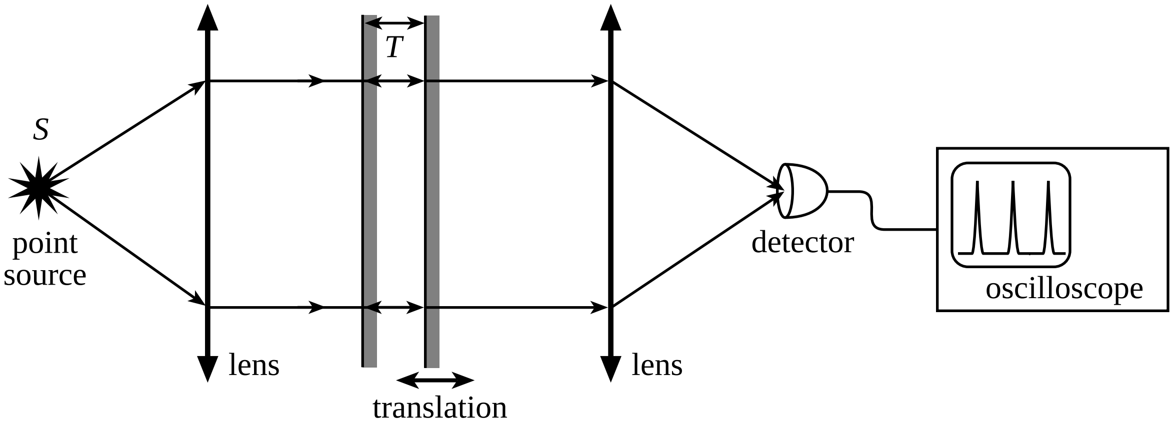
Testing a lens



Lens testing is particularly important for quantifying aberrations and measuring focal length.

4. Scanning Fabry-Perot Interferometer

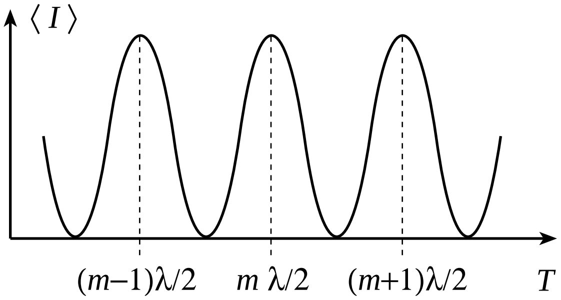
This interferometer is simply an *actual* folded Twyman-Green interferometer! It is the collimated-light version of the Fabry-Perot etalon. Usually Fabry-Perot interferometers are used to measure the spectrum (intensity vs. frequency or wavelength) by scanning the separation T between the two partially reflecting mirrors.



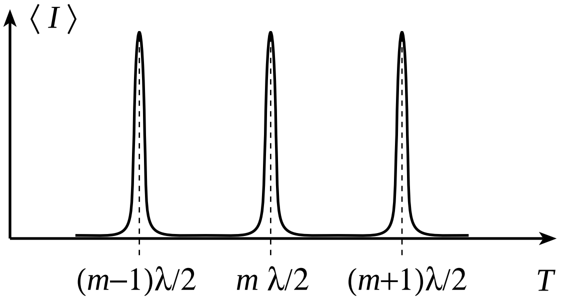
Since constructive interference occurs when

$$T = m\lambda_0/2 \quad \Rightarrow \quad \text{constructive interference},$$

then a large signal occurs at the detector every time the thickness T is scanned through an integer number of half wavelengths. For weakly reflecting mirrors, the intensity $\langle I \rangle$ vs. thickness T thus looks like the plot below on the left.



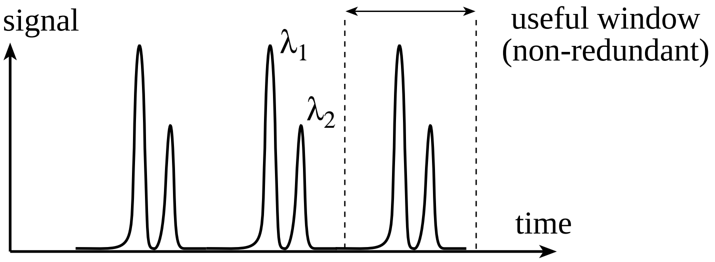
2-wave interference



multiple-wave interference

However, generally a scanning Fabry-Perot contains very high-reflecting mirrors, and thus the light is reflected between the mirrors multiple times — we can no longer assume the interference is dominated by only 2 waves as we did in Section III.C.2. Without deriving this result in detail, it turns out that the effect of multiple reflections is to cause the peaks associated with constructive interference to become narrower, as shown above on the right.

With narrower peaks, we can <u>resolve</u> more closely spaced wavelengths. For example, if we scan T as a function of time when a 2 wavelength source illuminates the interferometer, then the detector signal vs. time viewed on an oscilloscope might look like this:



5. Mach-Zehnder Interferometer

This interferometer is a variation of the Michelson/Twyman-Green style that makes it possible for:

(i) a <u>single-pass</u> of light through the test component;

(ii) convenient, simultaneous access to <u>both output beams</u>.