Lloyd’s Mirror

Another arrangement for producing an interference pattern with a single light source.

Waves reach point $P$ either by a direct path or by reflection.

The reflected ray can be treated as a ray from the source $S'$ behind the mirror.

An interference pattern is produced on the screen as a result of the combination of the direct ray (red) and the reflected ray (blue).
Interference Pattern from a Lloyd’s Mirror

This arrangement can be thought of as a double-slit source with the distance between points $S$ and $S'$ comparable to length $d$.

An interference pattern is formed.

The positions of the dark and bright fringes are reversed relative to the pattern of two real sources.

This is because there is a 180° phase change produced by the reflection.
Phase Changes in Reflection

- A wave on a string reflects from a fixed endpoint with reversed phase.
- A wave on a string reflects from a sliding endpoint without a phase change.
- Light reflects with/without a phase change from a medium with higher/lower refractive index. (This follows from continuity of the sum of incident, reflected, and transmitted field strengths.)
Interference in Thin Films

Interference effects are commonly observed in thin films.

- Examples include soap bubbles and oil on water

The various colors observed when white light is incident on such films result from the interference of waves reflected from the two surfaces of the film.

Facts to remember:

- An electromagnetic wave traveling from a medium of index of refraction $n_1$ toward a medium of index of refraction $n_2$ undergoes a $180^\circ$ phase change on reflection when $n_2 > n_1$.
  - There is no phase change in the reflected wave if $n_2 < n_1$.

- The wavelength of light $\lambda_n$ in a medium with index of refraction $n$ is $\lambda_n = \lambda / n$ where $\lambda$ is the wavelength of light in vacuum.
Interference in Thin Films

Assume the light rays are traveling in air nearly normal to the two surfaces of the film.

Ray 1 undergoes a phase change of 180° with respect to the incident ray. Ray 2, which is reflected from the lower surface, undergoes no phase change but travels an additional distance of 2t before the waves recombine.

For constructive interference and normal incidence

\[ 2nt = (m + \frac{1}{2})\lambda \quad (m = 0, 1, 2 \ldots) \]

For destructive interference, \[ 2nt = m\lambda \quad (m = 0, 1, 2 \ldots) \]
Interference in thin films, non-normal incidence

\[ AB = BC = \frac{d}{\cos(\theta_2)} \]

\[ AD = 2d \tan(\theta_2) \sin(\theta_1) \]

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

\[ OPD = n_2 (AB + BC) - n_1 (AD) \]

\[ OPD = n_2 \left( \frac{2d}{\cos(\theta_2)} \right) - 2d \tan(\theta_2) n_2 \sin(\theta_2) \]

\[ OPD = 2n_2 d \left( \frac{1 - \sin^2(\theta_2)}{\cos(\theta_2)} \right) \]

\[ OPD = 2n_2 d \cos(\theta_2) \]

- Constructive interference if: \[ 2n_2 d \cos(\theta_2) = m\lambda \]
Interference in floating films

Light reflecting from the top surface of the film undergoes a 180° phase change. This is equivalent to shifting the wave by half a wavelength.

Light reflecting from the bottom surface of the oil film has no phase change, but it travels an extra distance of half the wavelength of red light. Red light reflected from the top surface interferes constructively with red light from the bottom surface, so the film looks red. Light of other colors experiences destructive interference.
Anti-reflection coatings

Light reflected from both the top and bottom surfaces of the coating undergoes a 180° phase change. This is equivalent to shifting both waves by half a wavelength.

The thickness of the coating is 1/4 of the wavelength of green light in the coating material.

Light reflecting from the bottom surface travels an extra distance of half the wavelength of green light. Green light reflected from the top surface interferes destructively with green light from the bottom surface; in other words, all the green light, and most of the light in the middle of the visible spectrum, is transmitted. Some red and violet light is reflected, so the coating looks purple.
Interference in Thin Film, Soap Bubble Example
Newton’s Rings

Another method for viewing interference is to place a plano-convex lens on top of a flat glass surface.

The air film between the glass surfaces varies in thickness from zero at the point of contact to some thickness \( t \).

A pattern of light and dark rings is observed.

- These rings are called Newton’s rings.
- The particle model of light could not explain the origin of the rings.

Newton’s rings can be used to test optical lenses.
Optical quality testing

- Fringes (light and dark lines) occur for monochromatic light reflected by a variable gap between two surfaces.

- Deviations from straightness of these fringes reveal features of the surfaces smaller than a wavelength of light.

FIGURE 32: If both surfaces are flat, the interference lines are straight (A). If one or both surfaces are curved, the dark lines of destructive light interference will form circular (B, C), if a surface possesses rotational symmetry. Surface irregularities will show as deviation of the interference lines from either straight, curved or circular line form, and can be measured to a small fraction of a wavelength.
Michelson Interferometer, Schematic

A ray of light is split into two rays by the mirror $M_0$.

- The mirror is at 45° to the incident beam.
  - The mirror is called a *beam splitter*.
  - It transmits half the light and reflects the rest.

The reflected ray goes toward mirror $M_1$.

The transmitted ray goes toward mirror $M_2$.

The two rays travel separate paths $L_1$ and $L_2$.

After reflecting from $M_1$ and $M_2$, the rays eventually recombine at $M_0$ and form an interference pattern.
The standard interferometer uses a partially reflecting/partially transmitting mirror to create two coherent light beams.

The beams are reflected from two mirrors and superposed and interfere.

The central parts of the beams will interfere constructively if the path length difference is an integral multiple of a wavelength.

The interference pattern is sensitive to motion of either mirror by a fraction of a wavelength.

The fringe pattern shifts by one-half fringe each time either mirror is moved a distance $\lambda/4$. 
General relativity predicts the existence of gravitational waves.

In Einstein’s theory, gravity is equivalent to a distortion of space. These distortions can then propagate through space.

The LIGO apparatus is designed to detect the distortion produced by a disturbance that passes near the Earth.

The interferometer uses laser beams with an effective path length of several kilometers.

At the end of an arm of the interferometer, a mirror is mounted on a massive pendulum.

When a gravitational wave passes, the pendulum moves, and the interference pattern due to the laser beams from the two arms changes.