Applications of interferometers

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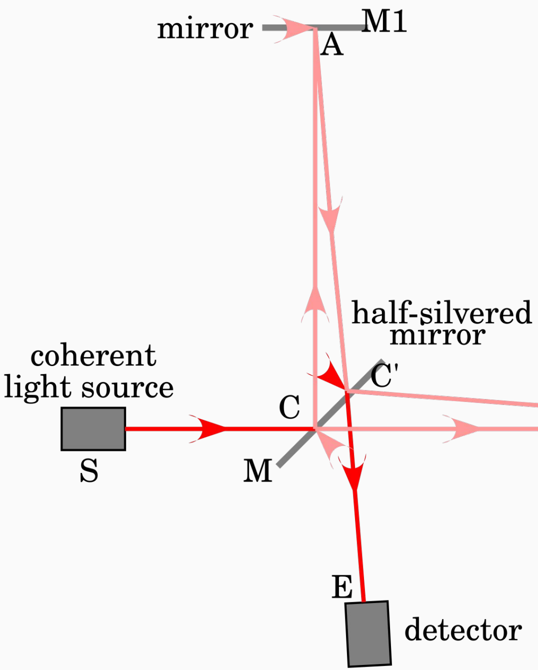
What are interferometers?

- One of the most important instruments in laser spectroscopy are interferometers
- Interferometers are investigative tools used in many fields of science and engineering
- They are called interferometers because they work by merging sources of light to create an interference pattern, which can be measured and analyzed: hence 'Interfere-meter', or interferometer

Interferometers

- Interferometer in which only two partial beams interfere are the Michelson interferometer and the Mach–Zehnder interferometers
- Multiple-beam interference is used in Fabry–Perot interferometer

Michelson interferometer



- The laser beam is split into two orthogonal paths
- The interference of the two beams yields an oscillation of light beam intensity.

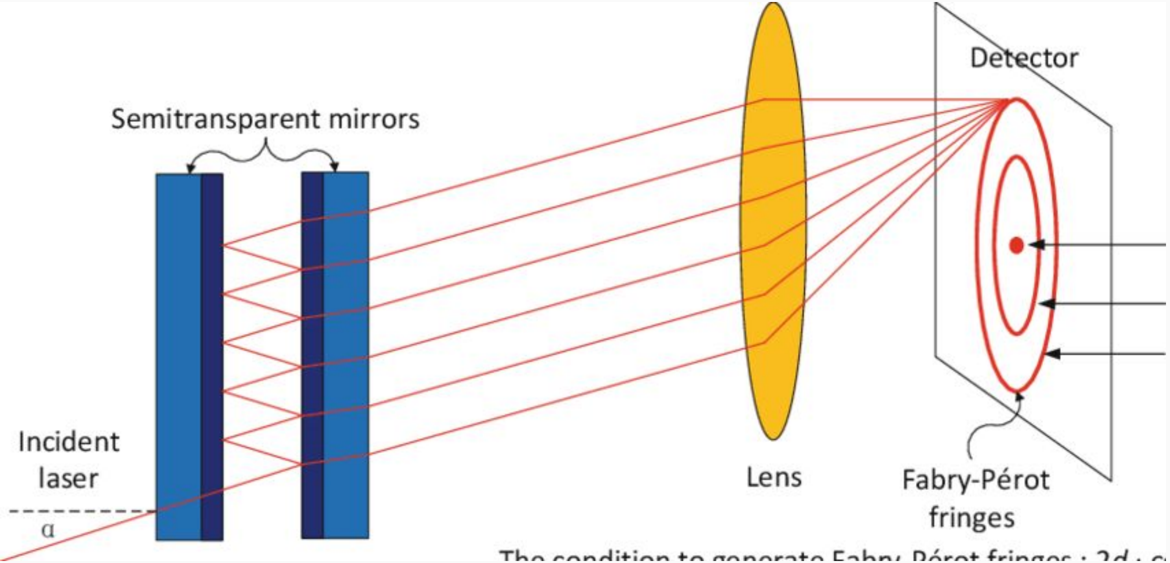
Michelson interferometer

- When the two beams recombine,
  - If their optical paths are equal ($2d1=2d2$), bright fringes appear.
  - If the paths differ ($2d1 \neq 2d2$), dark or alternating fringes form.
- Moving mirror M1 or M2 changes d1 or d2, causing the interference fringes to shift

Michelson interferometer

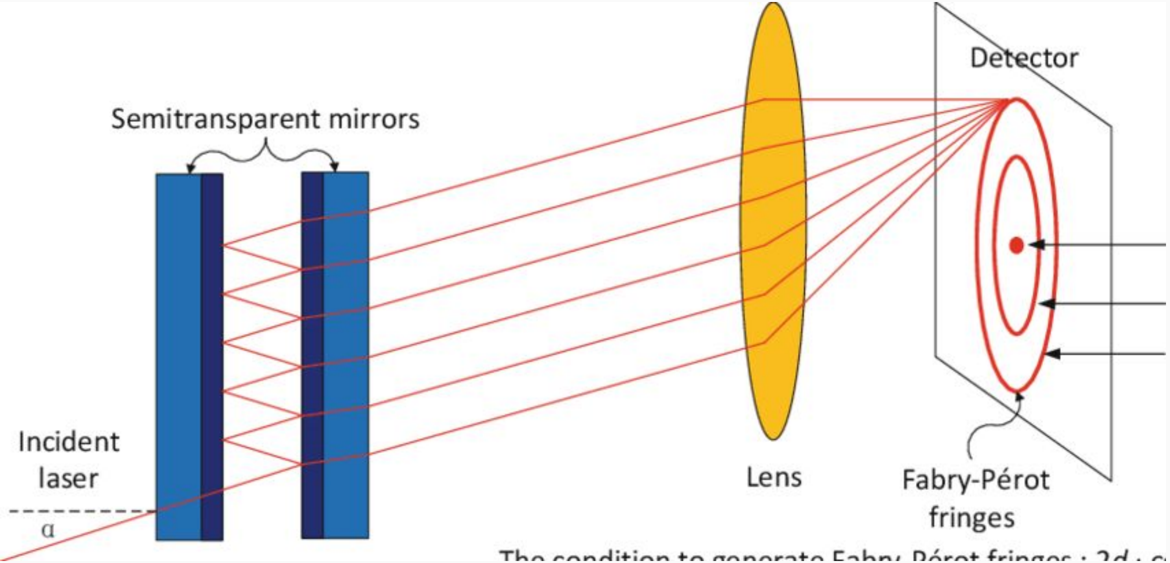
- If any mirror is moved along a distance Δy
- The optical path difference and phase difference changes by:
  $\Delta S = 2n\Delta y$, $\Delta\phi = 2n\Delta S/\lambda$
- Can be used for wavelength measurement by counting number of maxima in the detector: $\lambda = 2n\Delta y/N$

Fabry-Perot Interferometer



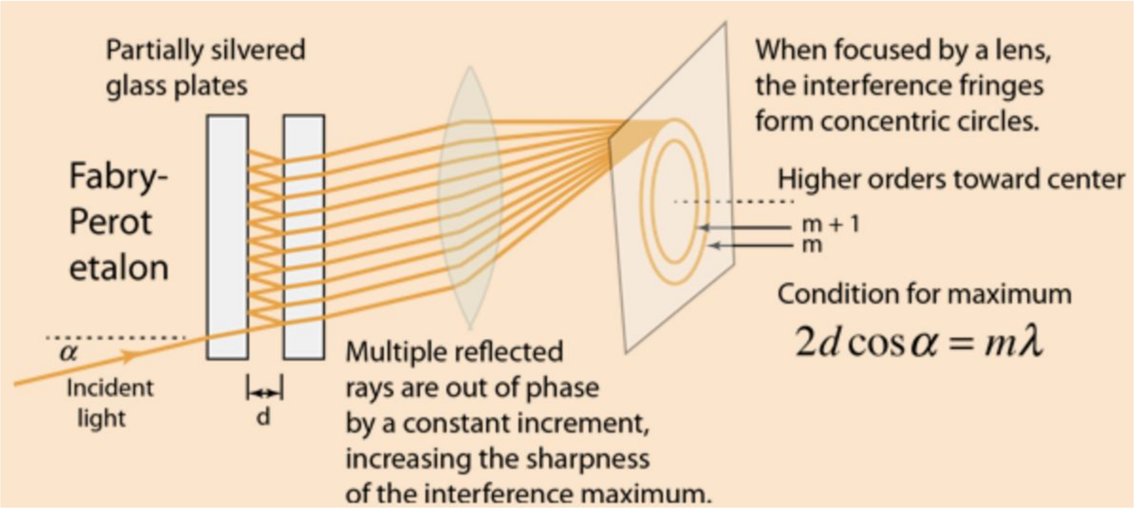
- This interferometer makes use of multiple reflections between two closely spaced semi-transparent mirrors

Fabry-Perot Interferometer



- 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.

Fabry-Perot Interferometer



- the Fabry-Perot Interferometer has a resolvance of: $\lambda/\Delta\lambda = m\pi\sqrt{r}/(1-r)$
- Where m is the order of interference and r is the reflectance of the mirrors
- Free spectral range: $\delta\lambda = \lambda^2/2d$

Applications:

LIGO and VIRGO are Gravitational Waves detectors which uses Michelson interferometry

Gravitational wave detection

- Gravitational waves are ripples in the fabric of spacetime, and are expected to be emitted by spinning stars in binary systems, black holes, massive stellar explosions
- Gravitational waves cause spacetime itself to oscillate, alternately stretching in one direction while compressing in a perpendicular direction. This oscillations last as long as the wave is passing.

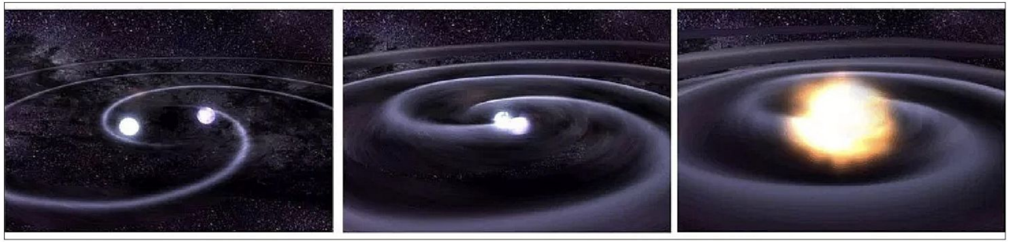
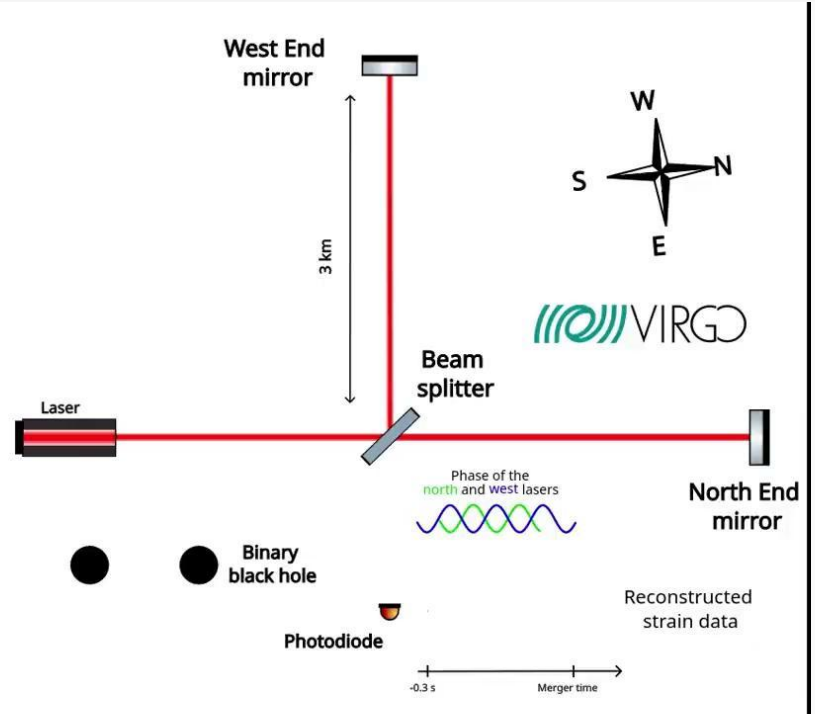


Figure 1: Artist's impression of the merging phase of a binary neutron star system emitting gravitational waves (image credit:NASA/CXC/GSFC/T. Strohmayer)

Detection technique

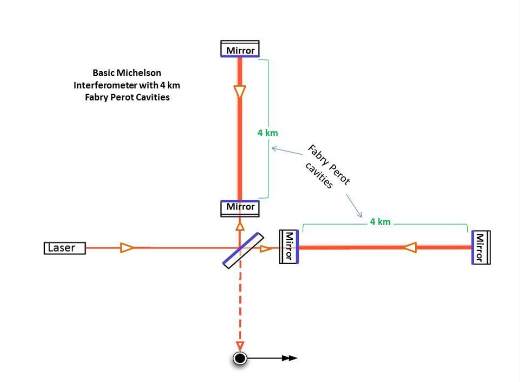
- The two beams of laser light coming from the two arms, are recombined **out of phase (destructive interference)** on a detector so that, in principle, no light reaches the detector.
- The variation of the optical path length, caused by the changing distance between the mirrors, produces a very small phase shift between the beams and, thus, a variation of the luminous intensity, which is proportional to the wave's amplitude.

Detection technique



Gravitational wave detection

- The long arms of these detectors (LIGO-4km & VIRGO-3km) seems enormous but they would still be too short to enable the detection of gravitational waves
- This was solved by including "Fabry Perot cavities" in the Michelson interferometer



Fabry–Pérot cavity

- In gravitational wave detection, a Fabry–Pérot cavity is used to store photons for almost a millisecond while they bounce up and down between the mirrors.
- This increases the effective distance traveled by each laser by ~ 300 times. With this longer length, the absolute change by gravitational waves is bigger. Increases detectability.
- This also increases the time a gravitational wave can interact with the light, which results in a better sensitivity at low frequencies.

Fabry–Pérot cavity

1. Optical Path Length Enhancement

- In a Fabry-Perot cavity, light reflects multiple times between two highly reflective mirrors, effectively increasing the optical path length. This amplification is quantified by the finesse (F) of the cavity, defined as:
  $F = (\pi\sqrt{R})/(1-R)$
  Where R is the reflectivity of the mirrors

Fabry–Pérot cavity

2. Signal-to-Noise Ratio Improvement

- By increasing the effective interaction time between the light and the gravitational wave-induced perturbations, Fabry-Perot cavities enhance the signal-to-noise ratio (SNR) of the detector. The SNR improvement is approximately proportional to the square root of the finesse:
  $\mathrm{SNR} \propto \sqrt{F}$
  This relationship indicates that higher finesse leads to better sensitivity in detecting gravitational waves.

Fabry–Pérot cavity

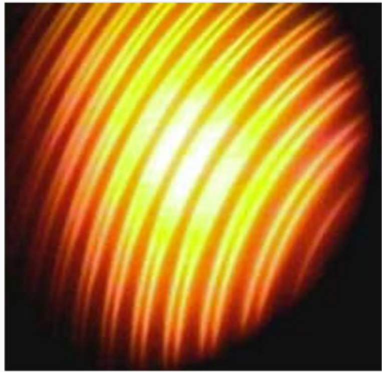
Practical implementation

- For instance, with a physical arm length of LIGO 4 km and a finesse of approximately 300, the effective optical path length becomes:
  $L = Ƒ \times L_{physical} \sim 300 \times 4\ km = 1200\ km$
  This substantial increase allows the detectors to measure incredibly small displacements, on the order of 10^{-18} meters, corresponding to the strain caused by distant astrophysical events

Applications

Fabry-Perot interferometers has been valuable tool for high-resolution spectroscopy

- A famous high resolution use of Fabry-Perot took place in the separation of sodium yellow doublet of wavelengths 588.9950 nm and 589.5924 nm
- Sodium doublet experiment
- We can see the two lines repeated for different order



Applications

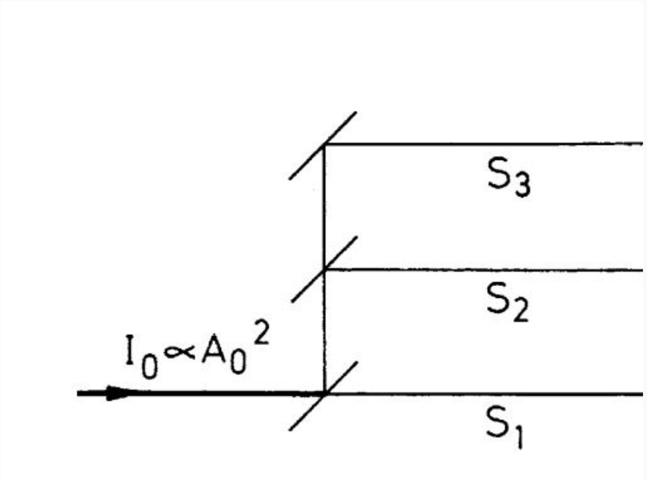
- Some other examples are ISRO's Mars Orbiter Mission (MOM), The Methane Sensor for Mars (MSM) instrument was designed and built at the ISRO Satellite Centre (ISAC).
- It is a Fabry-Pérot interferometer, an instrument that studies radiation by bouncing it between two partially silvered mirrors. With each bounce, some of the radiation escapes the mirrors and is collected at a point.
- Over multiple bounces, different parts of the same stream of radiation are collected as different waves of radiation, which are then made to interfere with each other to produce an interference pattern.
- The higher the reflectivity of the mirrors, the finer the pattern, and so the better it reveals important properties of the radiation.

Thank you

Backup slides →

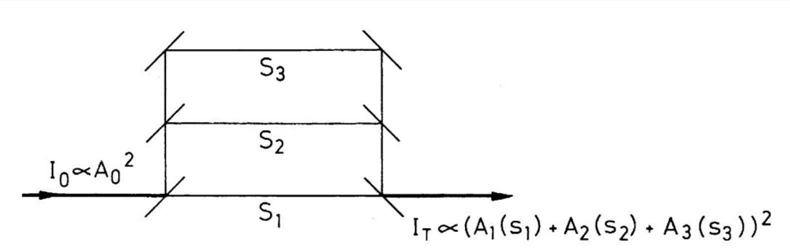
Basic principles

- Incident light of intensity I° which is divided into partial beams passing through different optical path lengths



Basic principles

- Each partial beam has an amplitude A_k with optical path length $s_k = nx_k$, where n is the refractive index A_k
- The total amplitude of the superpositions depends on the the amplitudes and phases: $\phi_k = \phi_o + 2\pi s_k/\lambda$



- The maximum intensity of the transmitted wave is achieved when all the partial waves constructively interfere

Application of Michelson interferometer

Some of the examples are LIGO and VIRGO experiment

- Gravitational waves cause spacetime itself to oscillate, alternately stretching in one direction while compressing in a perpendicular direction. This oscillations last as long as the wave is passing.
- Hence the two beams travel different distances in the two arms resulting in interference pattern called ‘fringes’

Fabry–Pérot interferometer

- Fabry-Perot interferometer is an optical cavity made from two parallel reflecting surfaces
- Optical waves can pass through the optical cavity only when they are in resonance with it