Optics E-5730 Spring 2020

Interferometry

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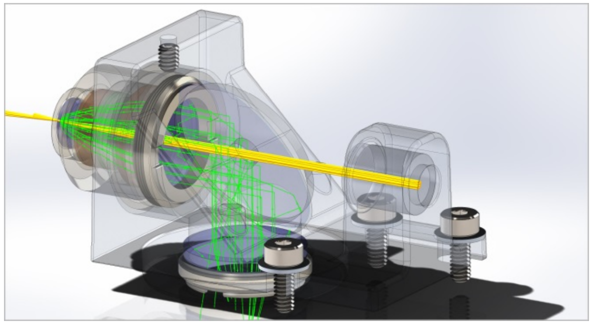
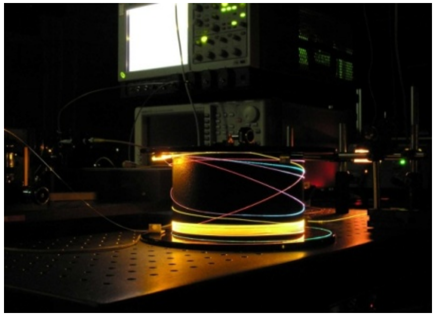
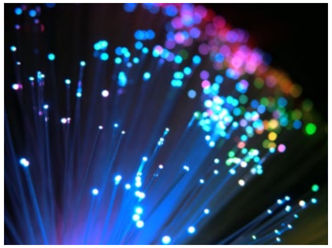
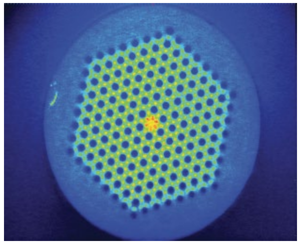
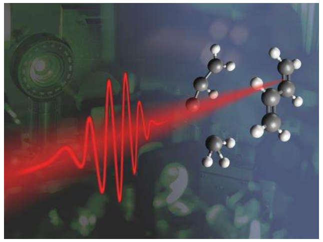



Last Lecture – Radiometry

- Radiometric units
- Blackbody radiation
- Reference detectors

This Lecture – Interferometry

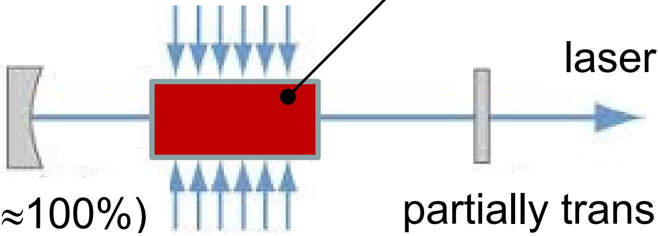
- Laser ABC
- Intensity correlation
- Applications of interferometry and different interferometers:
    - Michelson interferometer for length measurements
    - Mach-Zender interferometer
    - Sagnac interferometer
    - Fabry-Perot interferometer

Laser ABC

Laser (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation)

Laser’s main components are:

1. medium that can sustain population inversion, ’laser material’
2. optical resonator (mirror cavity)
3. external energy source creating population inversion (electricity, light, e.g., flash lamp)



laser material

laser’s output beam

mirror (R≈100%)

partially transparent mirror (T ~10-30%)

extrenal excitation energy

Laser’s most remarkable properties:

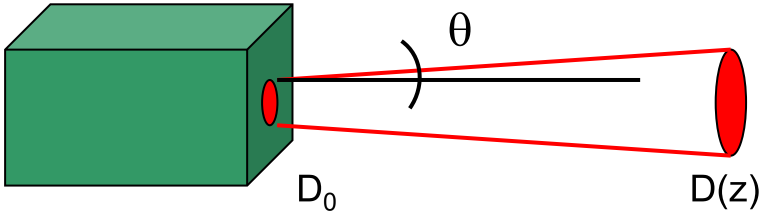
- ability to produce very monochromatic light
- ability to produce coherent light, i.e., all waves have identical phase
- very large spectral radiance:

$$L_\lambda = \frac{P_A}{\Delta\lambda \Delta\Omega \cos\theta}$$

- small beam divergence, caused by the high-quality optical resonator

Divergence of a Laser Beam

Any real beam of light, including lasers, is never perfectly collimated but diverges. The divergence is typically given as the half-angle θ:

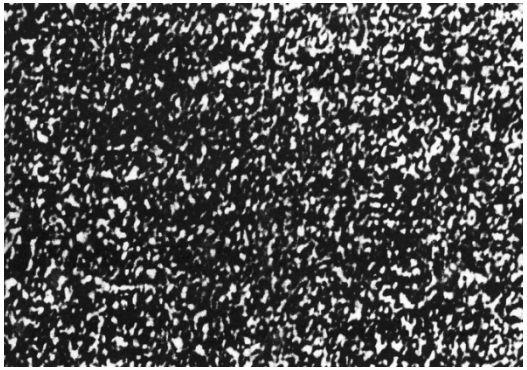


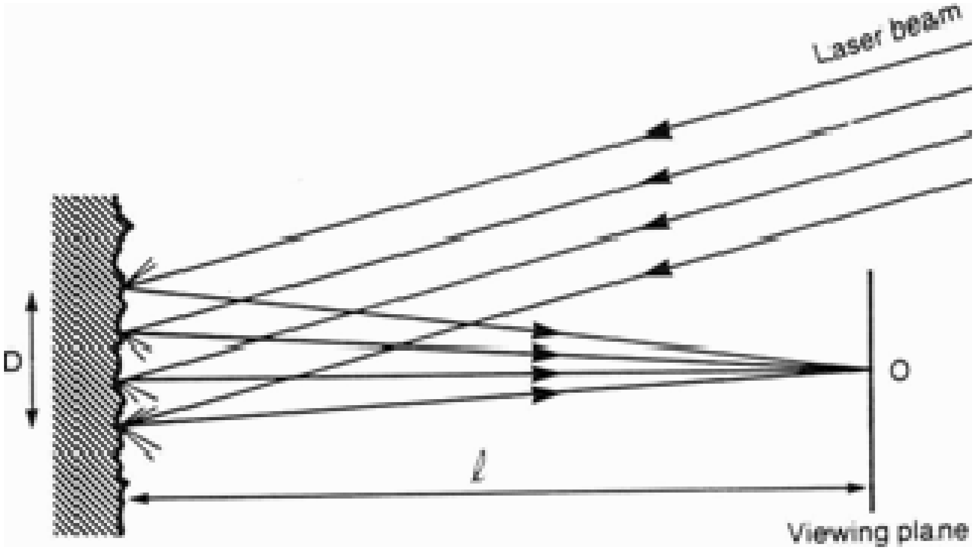
- for example, a high quality Helium-Neon laser beam has a divergence of 0,5 mrad (0,03°) and D_0 = 1 mm: at 10 meter distance the beam diameter D(z=10m) = 11 mm
- the solid angle of a diverging beam: $\Omega \approx 2\pi(1-\cos\theta)$
  for the above example $\Omega = 7{,}9 \times 10^{-7}$ (sterad) or $\Omega/4\pi \approx 10^{-7}$

Population Inversion and Emission Linewidth of a Laser

Laser Speckle

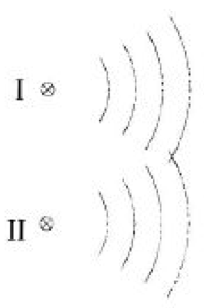
- formed when laser light illuminates rough surface
- physics: rays reflecting from different heights of the surface (surface roughness) interfere

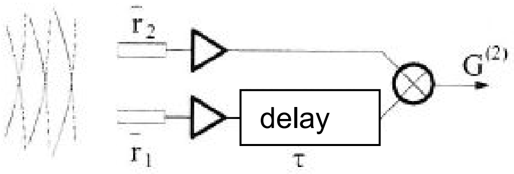




Intensity correlation $G^{(2)}$

incoherent
light sources





definition

$$G^{(2)}\left(\vec{r}_1,\vec{r}_2,t_1,t_2\right)=\left\langle I_1\left(\vec{r}_1,t_1\right)I_2\left(\vec{r}_2,t_2\right)\right\rangle$$

if $I_I = I_{II} = I_0$:

$$I\left(\vec{r},t\right)=2I_0\left[1+\cos\left(\Delta\bar{k}\cdot\bar{r}-\Delta\omega t+\Delta\phi\right)\right]$$

Let us place I(**r**,t) into the definition of $G^{(2)}$

Intensity correlation $G^{(2)}$

$$G^{(2)}\left(\vec{r}_1,\vec{r}_2,t_1,t_2\right)=\left\langle I_1\left(\vec{r}_1,t_1\right)I_2\left(\vec{r}_2,t_2\right)\right\rangle$$

$$I\left(\vec{r},t\right)=2I_0\left[1+\cos\left(\Delta\bar{k}\cdot\bar{r}-\Delta\omega t+\Delta\phi\right)\right]$$

$$\left(1+\cos\alpha_1\right)\left(1+\cos\alpha_2\right)=1+\cos\alpha_1+\cos\alpha_2+\frac{1}{2}\cos\left(\alpha_1+\alpha_2\right)+\frac{1}{2}\cos\left(\alpha_1-\alpha_2\right)$$

for non-coherent sources $\Delta\phi$ fluctuates so only first and last term will remain

$$G^{(2)}\left(\vec{r}_1,\vec{r}_2,t_1,t_2\right)=4I^2\left[1+\frac{1}{2}\cos\left(\Delta\vec{k}\cdot\left(\vec{r}_1-\vec{r}_2\right)-\Delta\omega\left(t_1-t_2\right)\right)\right]$$

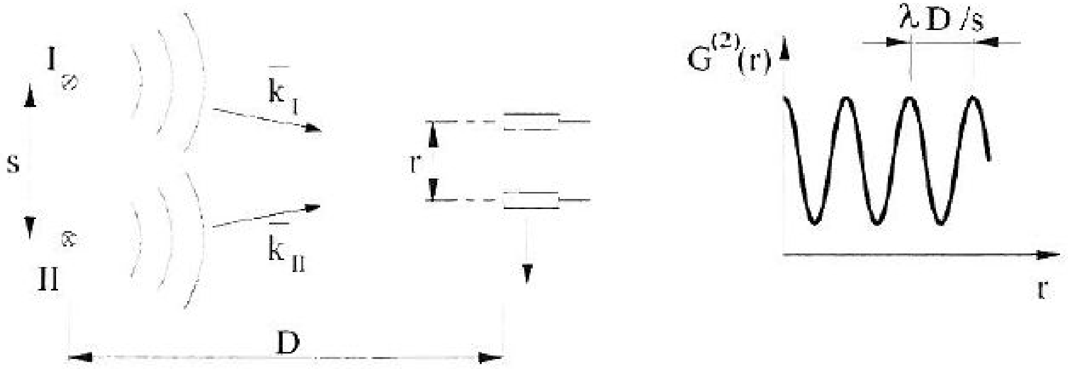
Like for Young's experiment: $\Delta k=\dfrac{2\pi s}{\lambda D}$

where s is the distance between the sources and

D is distance from sources to detectors

Intensity correlation $G^{(2)}$

$$G^{(2)}(r) = 4I_2\left[1+\frac{1}{2}\cos\left(\frac{2\pi s}{\lambda D}r\right)\right]$$

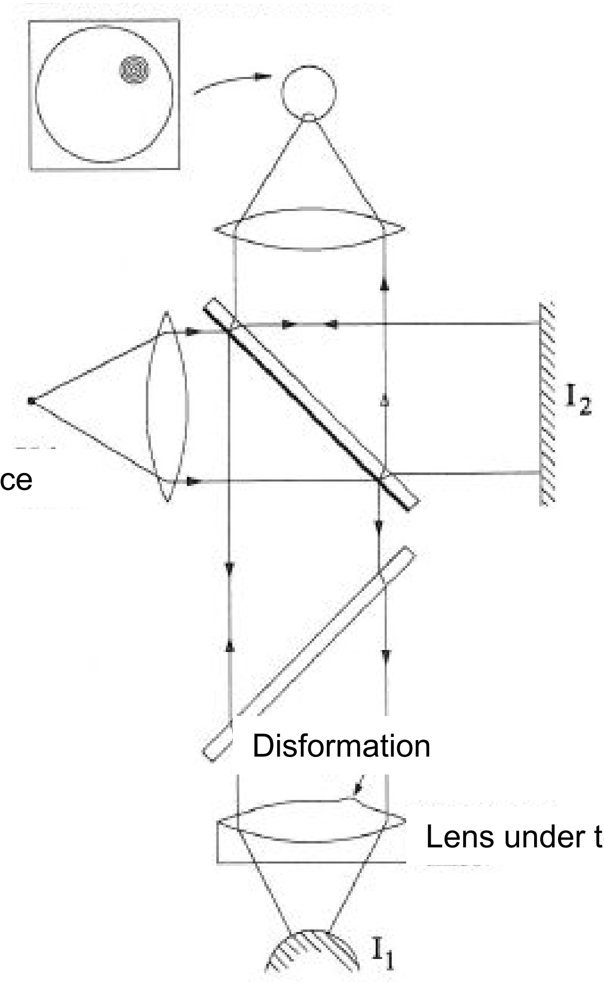


Example, the angular diameter of a star: λ = 1000 nm, D = 10 light years ≈ 10^{17} m and s = 100 x (diameter of the sun) ≈ 10^{11} m, so λD/s ≈ 1 m.

Thus for detector separation > 1 m the correlation decreases from which the diameter of the star can be estimated.

Applications of Michelson Interferometer I

Optical Surface Quality or Thickness Measurement



Observed interference pattern

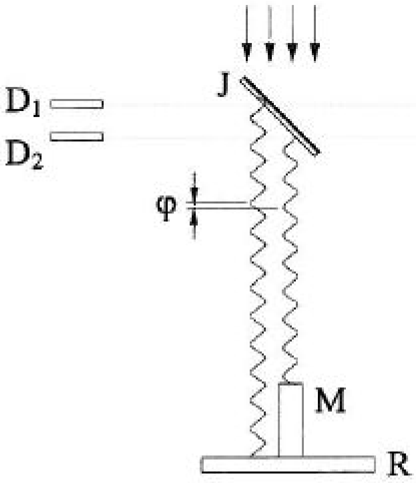
Light source

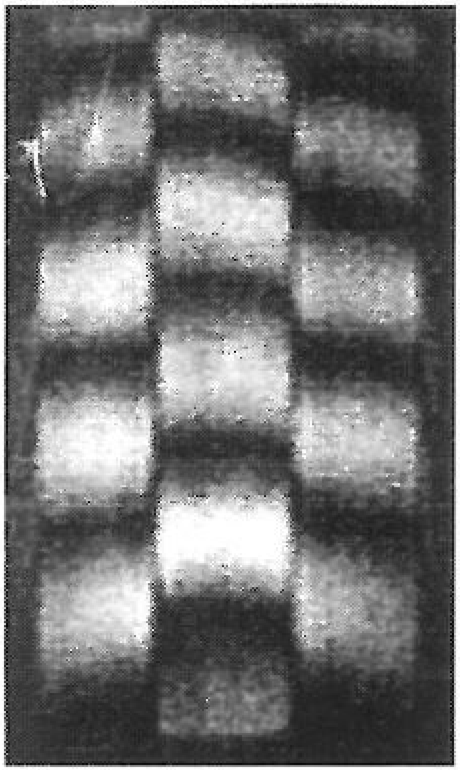
Disformation

Lens under testing

Applications of Michelson Interferometer II

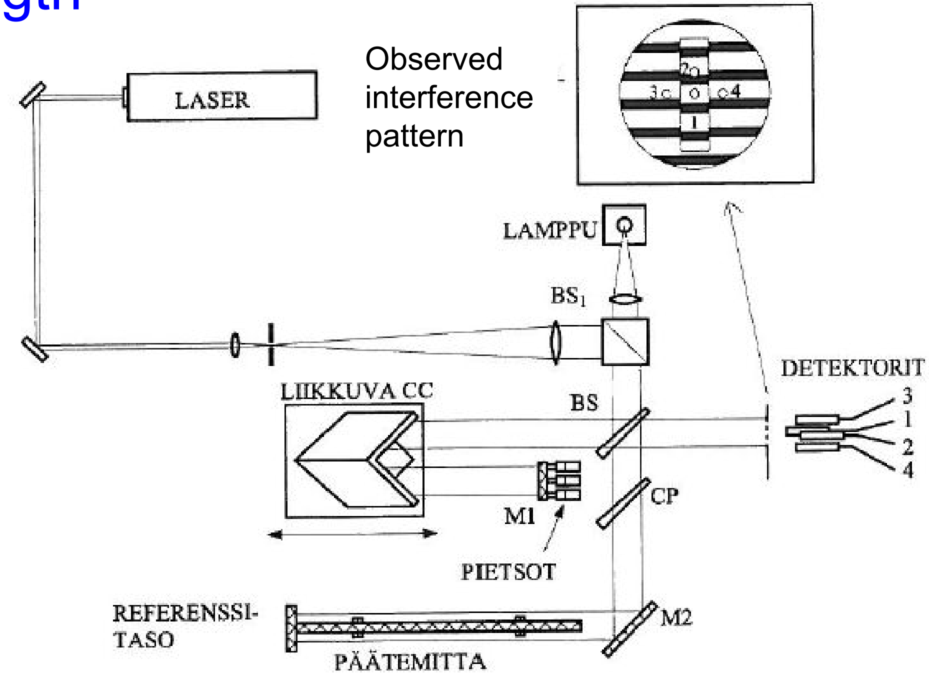
Metrology of Length



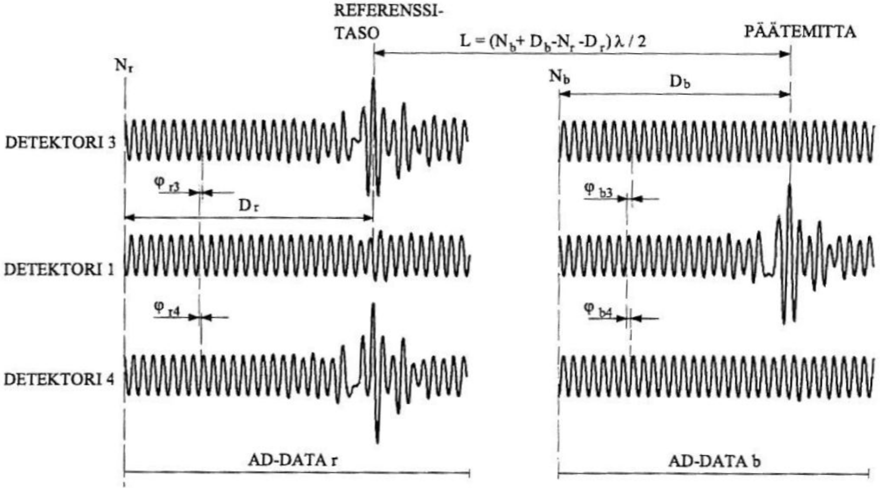


Applications of Michelson Interferometer II

Metrology of Length



Observed interference pattern

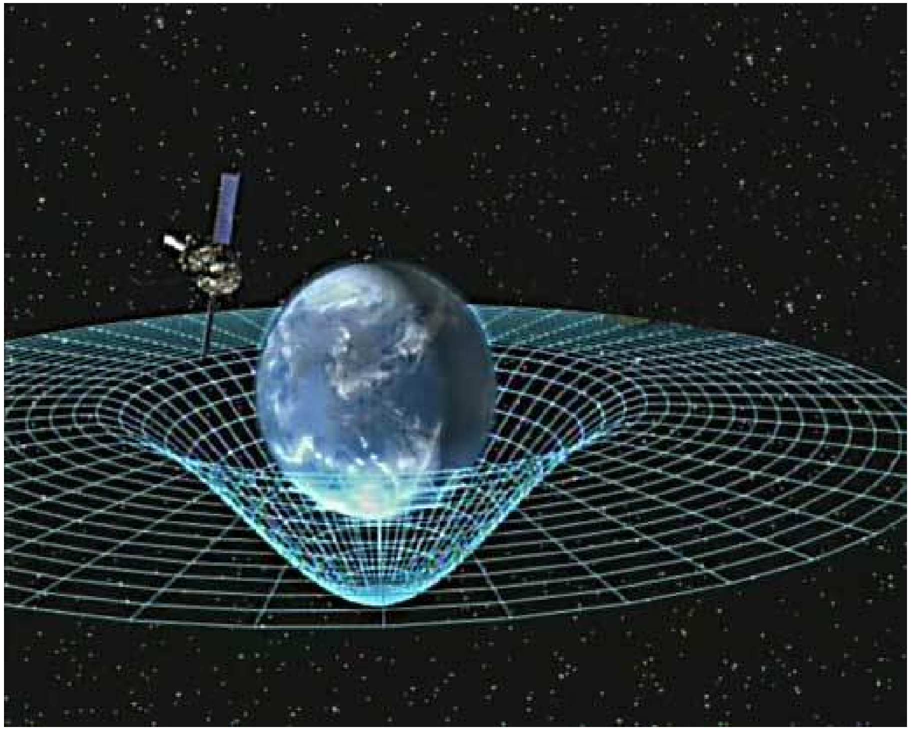


Applications of Michelson Interferometer III

Laser Interferometer Gravitational-Wave Observatory (LIGO)

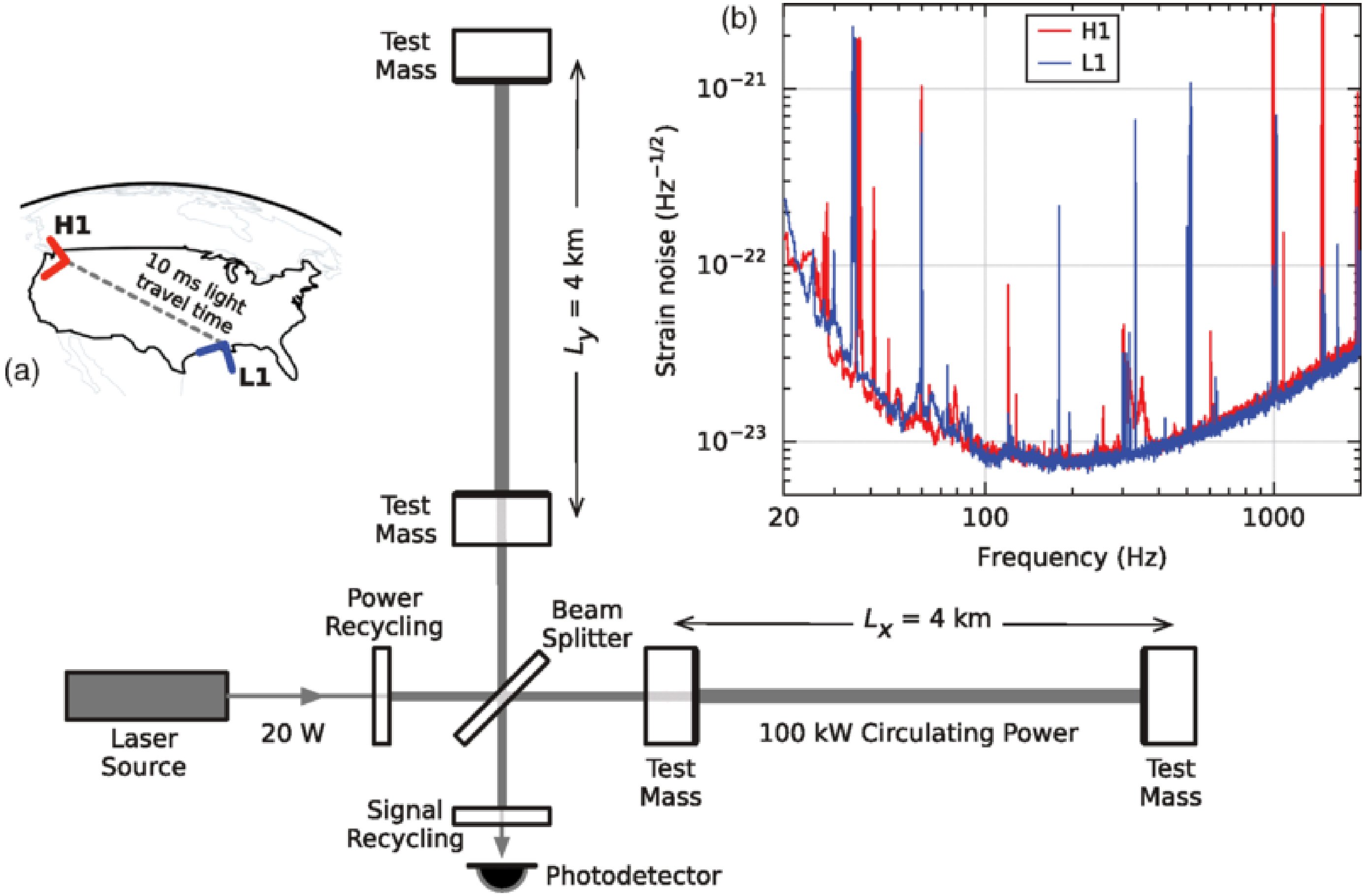
On 11 February 2016 LIGO and Italian Virgo collaborations announced the first detection of a gravitational wave

Laser Interferometer Gravitational-Wave Observatory (LIGO)



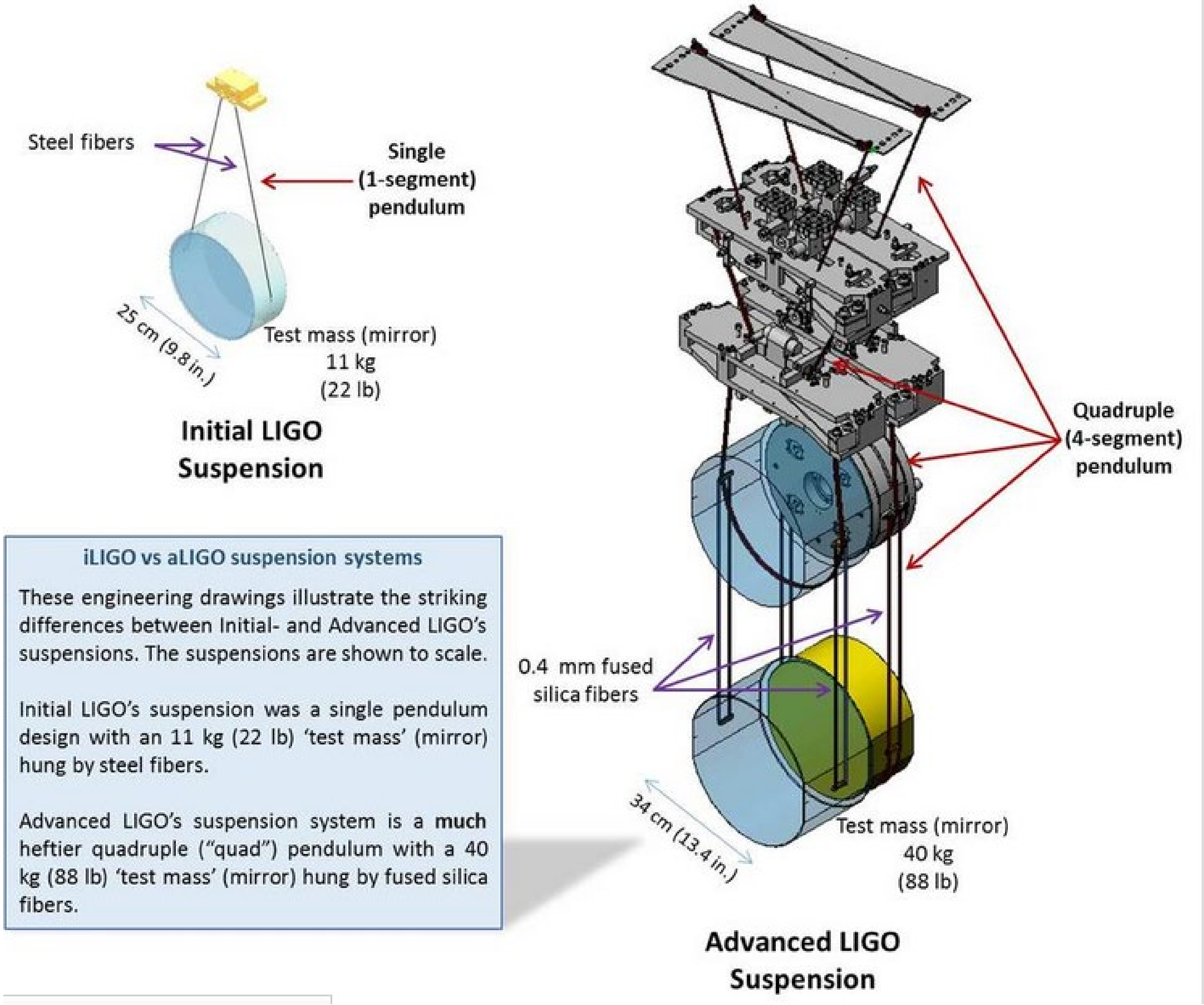
Gravitational waves are 'ripples' in the fabric of space-time caused by some of the most violent and energetic processes in the Universe which Albert Einstein predicted in 1916 (general theory of relativity). Massive accelerating objects, e.g., neutron stars or black holes orbiting each other, disrupt space-time in such a way that 'waves' of distorted space radiate from the source. Gravitational waves originating tens of millions of light years from Earth distort the 4 kilometer LIGO mirror spacing by about 10^{-18} m – less than one-thousandth the charge diameter of a proton. Equivalently this is a relative change in distance of approximately one part in 10^{21}.

Laser Interferometer Gravitational-Wave Observatory (LIGO)



A gravitational wave propagating through LIGO causes differential cavity length variations. Inset (a): Location and orientation of LIGO detectors at Hanford (H1) and Livingston (L1) USA. Inset (b): Instrument noise for each detector. The sensitivity is limited by photon shot noise at frequencies above 150 Hz and by a superposition of other noise sources at lower frequencies. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

Laser Interferometer Gravitational-Wave Observatory (LIGO)



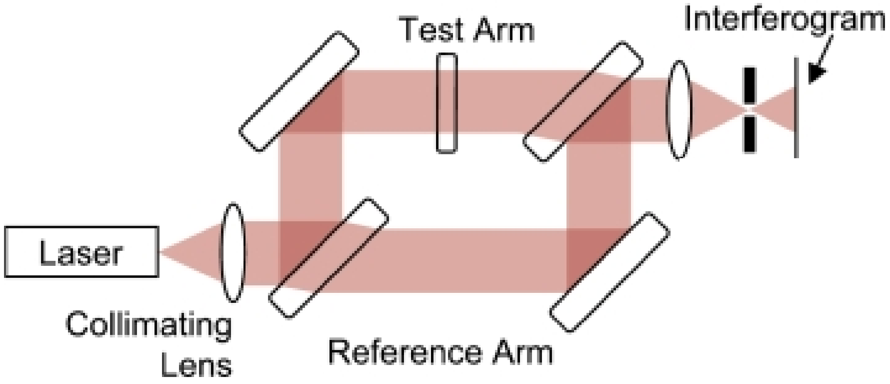
iLIGO vs aLIGO suspension systems

These engineering drawings illustrate the striking differences between Initial- and Advanced LIGO's suspensions. The suspensions are shown to scale.

Initial LIGO's suspension was a single pendulum design with an 11 kg (22 lb) 'test mass' (mirror) hung by steel fibers.

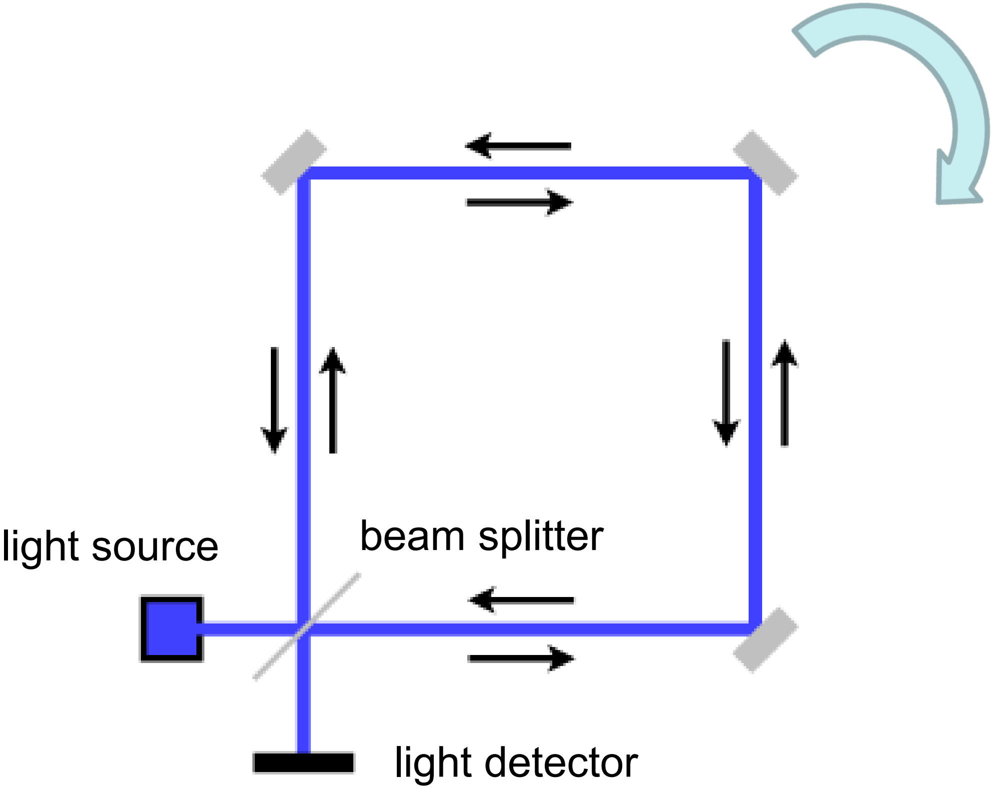
Advanced LIGO's suspension system is a **much** heftier quadruple ("quad") pendulum with a 40 kg (88 lb) 'test mass' (mirror) hung by fused silica fibers.

Mach-Zender Interferometer



Changing properties (pressure, temperature, flow) of the sample material (piece of glass, or a cuvette filled with gas or liquid) in the test arm change the optical path length in that arm with respect to the reference arm. Such changes can be observed as changes of the interference fringes in the interferogram.

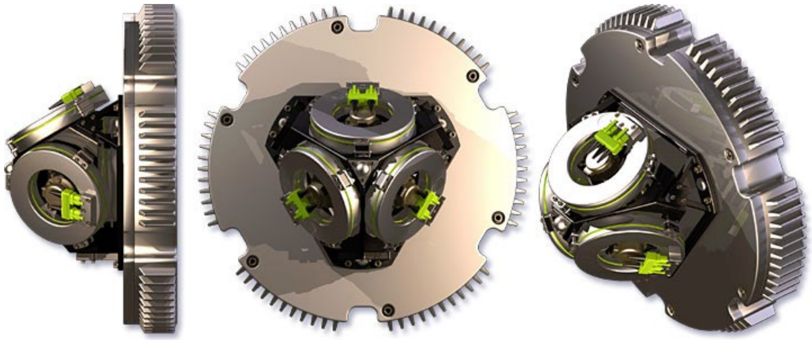
Sagnac Interferometer



What happens when the Interferometer rotates at angular speed Ω?

Sagnac Interferometer

Fibre-optic Sagnac interferometers are used as laser gyroscopes on board of planes, ships, submarines and satellites. Best laser gyroscopes deviate less than 0.01° in an hour.



Fabry-Perot Interferometer