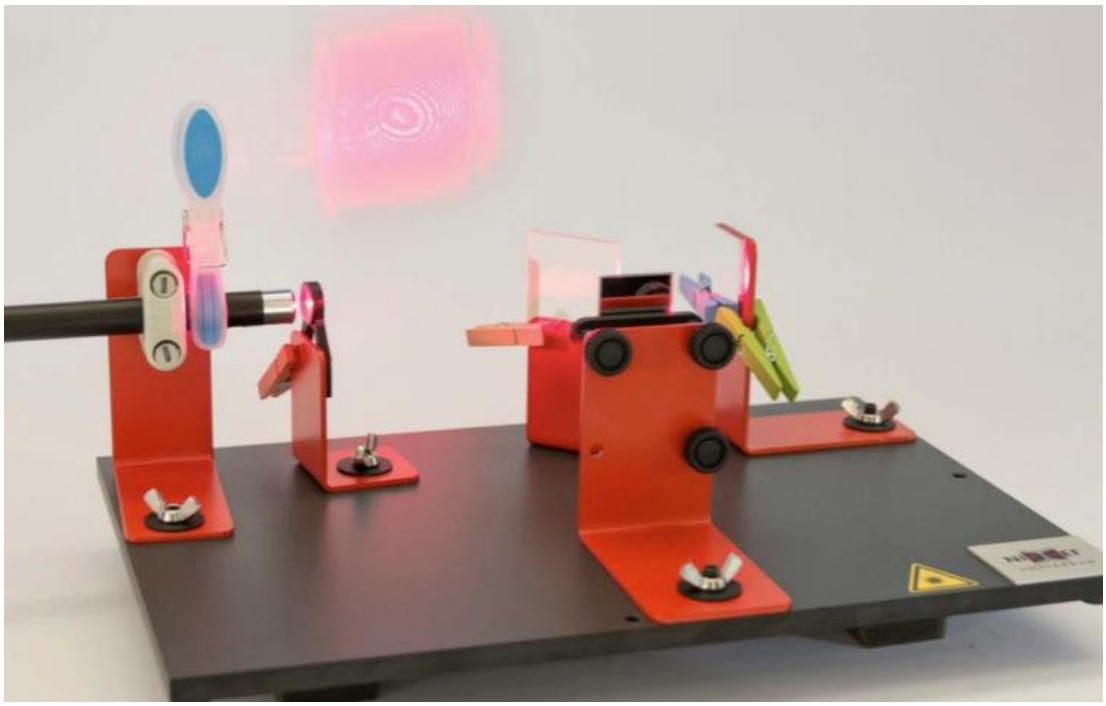
From the Michelson-Morley experiment to the gravitational-wave detection

Discovering and building a Michelson interferometer

FRONTIERS

PCCP demonstrator



Michelson interferometer from Nikhef – The Netherlands
Construction kit from H.Hennes

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Introduction: From the mysterious ether to gravitational-waves

Thanks to a small educational model, we will discover an optical device at the same time simple and extremely powerful and crucial for the history of science: the Michelson interferometer.

The Michelson interferometer was invented by the US physicist Albert Abraham Michelson, in the second half of the XIX century. Michelson was awarded the Nobel prize in 1907 for “his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid » (nobelprize.org)

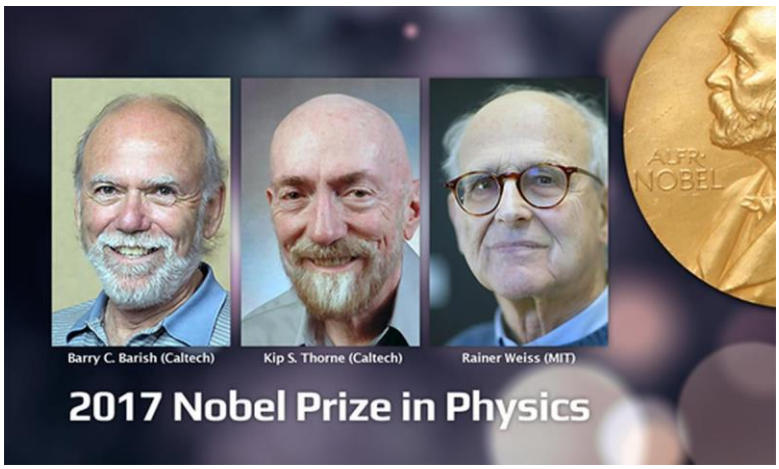
Albert Abraham Michelson,
Nobel prize in physics 1907

The Michelson interferometer was used by Michelson and his colleague Edward Williams Morley to attempt a demonstration of the existence of a form of matter, called “ether”, that physicists at the time believed to fill space and to be the propagation medium of electromagnetic waves.

Instead, the conclusion of the famous “Michelson-Morley experiment” performed in 1887, was exactly the opposite: there is no such thing as the ether. This was a pivotal step that prompted a crisis and a deep rethinking of classical physics. It was this experiment and its consequences that eventually led to the birth of Albert Einstein’s theory of special relativity in 1905.

Almost 130 years after that crucial moment, the Michelson interferometer has been used again by LIGO and Virgo to detect the first ever gravitational waves and to illuminate the sky thanks to a new cosmic messenger, alternative to electromagnetic waves.

The first gravitational-wave detection was defined as “a discovery that shocked the world”, by the Nobel prize committee, who awarded three founding fathers of the LIGO detector with the 2017 prize in physics.



Barish, Thorne and Weiss, Nobel prize 2017, for the detection of the Gravitaional-waves

Credit :nobelprize.org

Gravitational waves, ripples in the fabric of space-time predicted in 1905 by the general relativity theory, travel through the Universe at the speed of light and bring messages about very violent phenomena, as the mergers of black holes and neutron stars.

The Michelson interferometer connects 130 years of science history and two Nobel prizes, linking a fundamental test for special relativity to a fundamental test of general relativity.

The use of the Michelson interferometer will allow us, not only to speak about relativity, cosmic messengers and black holes, but also to become familiar with concepts such the wave nature of light and the concept of “interference”: the superposition of light beams, generating light with smaller or higher amplitude, or even a dark spot.

Moreover, the instrument will show us the incredible “power of interferometry” to measure distances with amazing precision.

Teacher Guidelines

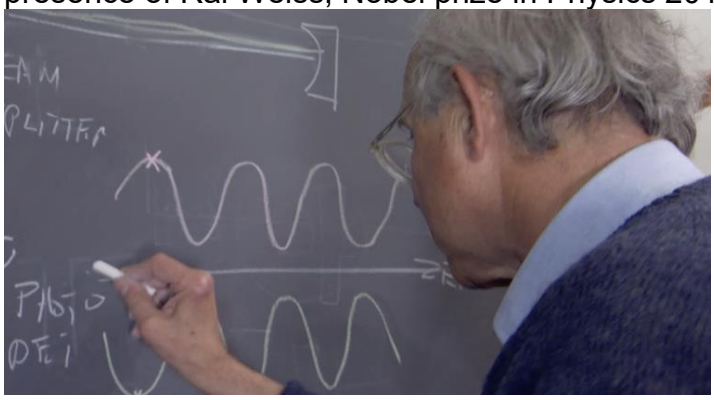
The Michelson-Morley experiment is very interesting from a) an historical point of view (birth of special relativity) and because it is an example of physics experiment of the “old times”, with a very poor technology (no laser light, no photodetectors, no computers…).

Physicists at the end of XIX century were searching for a proof of the existence of a transmission medium for light, since other waves are transmitted through a medium (acoustic waves through air or materials, seismic waves through the Earth crust and mantle, etc…).

An observer moving with respect to the ether, would measure a different speed of light, with respect to an observer at rest with respect to the ether. Since the Earth is moving around the sun at a speed of ~ 30 km/s (question for students: why don’t we feel this movement?), sending light beams in two orthogonal directions (one in the direction of the Earth movement and the second in the direction perpendicular to the Earth movement), we can measure the relative speed of light beams.

The result of the experiment was that there is no ether**: light travels at the same speed in all the direction and under all circumstances.** This had very deep consequences in the crisis of classical physics and in the development of the special relativity theory by Einstein.

Before we start, take a look at this video showing how the Michelson interferometer works in the context of gravitational-wave detection, with the presence of Rai Weiss, Nobel prize in Physics 2017



https://www.ligo.caltech.edu/video/IFO-response

Rai Weiss, Nobel Prize in Physics 2017 for the discovery of the gravitational waves, explaining interference and the theory of Michelson interferometers

Credit :LIGO

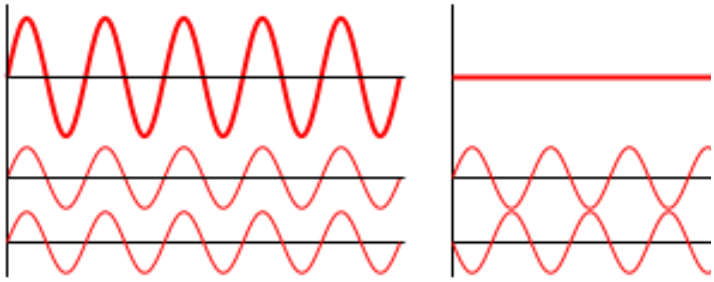
Introducing waves and interference

Before entering in more details on the Michelson interferometer, let's introduce the wave nature of light.

Light is an electromagnetic wave: it is composed by electric and magnetic fields oscillating and propagating and transporting energy. The visible light is a particular electromagnetic wave, whose frequency is comprised between 0.4 and 0.8 micrometers. At frequencies below the visible light, there is the infrared light, and at frequencies above the ultraviolet one.

Light is a wave. Waves have a particular property which make them very different from particles: interference.

If you put together two particles, the result will be a bigger particle. If you sum two waves, the total can be either a bigger wave, or a smaller wave, or even no wave at all. The picture below can explain how interference works.



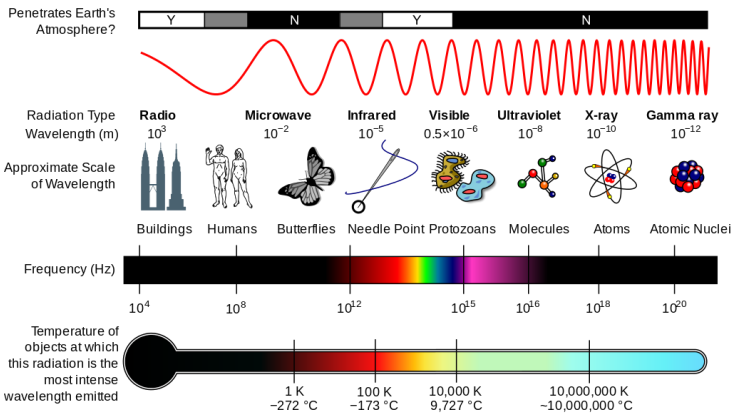
In the left panel, the superposition of two waves generates a bigger wave: the two waves are "in phase". In the right panel, on the other hand, the superposition of the same two waves, simply shifted along the x-axis, generate no wave: the waves are "out of phase". In the second example, since there is no wave at the end, we don't have any light, just darkness.

Think about how we use the expression in everyday life: if you are "in phase" with someone, you are in harmony and the sum of your efforts will achieve greater results that the single efforts. If you are not in phase, your respective efforts could cancel each other out.

TEACHERS GUIDELINES

Other kind of waves: Before speaking about electromagnetic waves, you can introduce other, more familiar, kind of waves: waves in a pond, acoustic waves, seismic waves. You can introduce concepts such as the wavelength, the frequency, the speed of the wave, and also the polarisation. With waves in a pond (or in a bucket in a classroom) you can also highlight the process of interference.

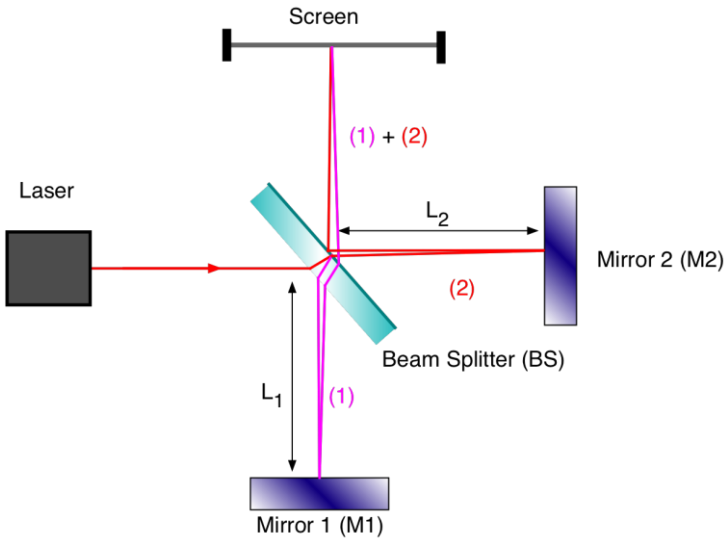
The Electromagnetic spectrum: it is interesting to take a look to the electromagnetic spectrum and, for each type of electromagnetic wave (visible, radio, etc…), identify the wavelength (and frequency), the phenomena or/and devices generating the waves (for instance: the UV are present in the sun light spectrum etc…).



Introducing the Michelson interferometer

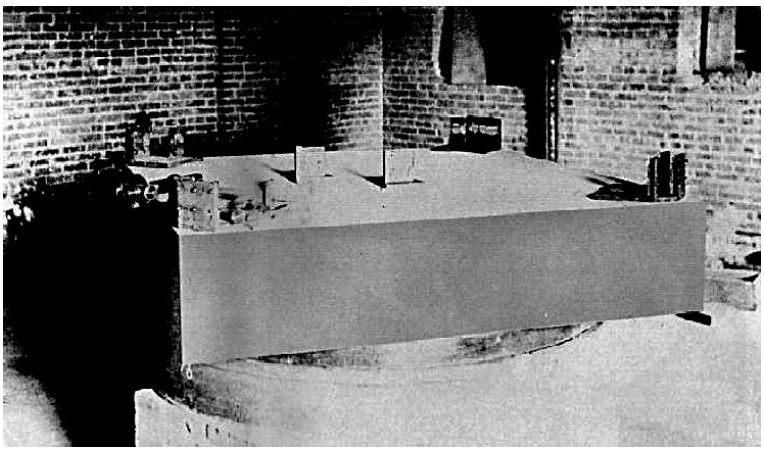
In a Michelson interferometer (see the picture), a light beam is split in two parts thanks to a semi-reflecting mirror, called a *beam-splitter*, that reflects half of the light at 90 degrees while allowing for the other half to pass through. This creates to light beams perpendicular to each other. The two light beams are sent to two mirrors, they are reflected from them and recombined on the beam splitter, where they interfere.
In modern interferometers we use lasers rather than standard light sources as Michelson and Morley did, but the working principle is the same.

The interference condition (to be “in phase” or “out of phase”, or “slightly in phase or out of phase”) depends on the two relative path lengths. If the first beam travels for a longer path with respect to the second, its phase will be slightly different. This phase difference changes the interference condition and, therefore, the optical power measured at the screen.



Watch again the video with Rai Weiss to understand how the variation of distance is transformed in a variation of luminosity on the screen of the interferometer by the interference.

https://www.ligo.caltech.edu/video/IFO-response



Define goals and/or questions from current knowledge

We will assemble a Michelson interferometer using a small construction kit developed by Nikhef, the Dutch National Institute for Subatomic Physics, a high-energy and astroparticle physics laboratory in Amsterdam, The Netherlands.

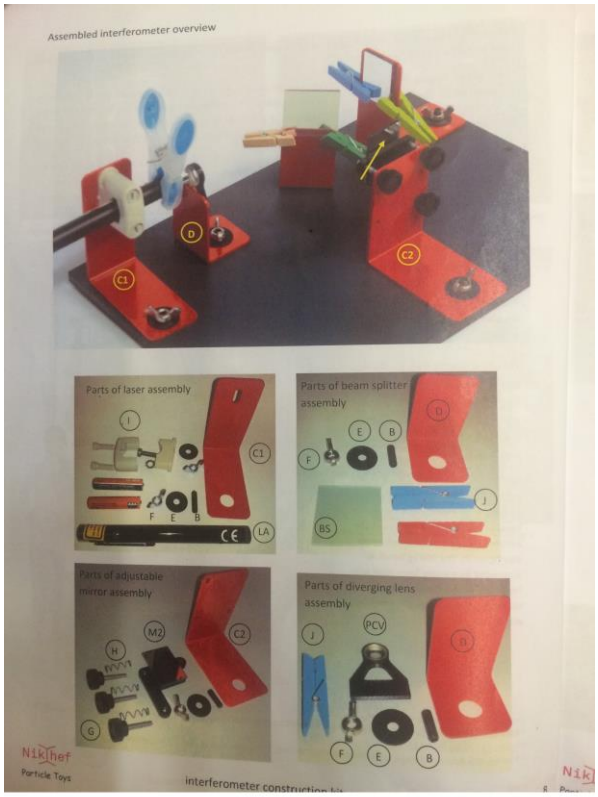
FOR THE TEACHERS: The Nikhef interferometer costs about 70 € + VAT. The same interferometer can obviously be built with simple optics material.

Build the instrument

Research is not only elaborate theories. It is also building ultra-sensitive instruments, able to test those theories. Michelson was awarded the Nobel prize for his instruments in 1907 as were the three founding fathers of LIGO in 2017.

We will build a Michelson interferometer, a supersensitive distance measurement device. The fundamental difference with a ruler, is that the Michelson interferometer does not measure the absolute distance, but the difference in lengths between two interferometer arms. The Nikhef construction kit contains:

- all the pieces needed to build the interferometer
- the instruction manual.



Follow the various steps of the construction of the instrument as explained in the manual and in the video below.

INSERT VIDEO HERE.

Once the interferometer is assembled, it should be aligned, until circular fringe patterns are observed.

Question: Why do we see these rings?

Planning & investigation

Plan investigation

First of all, observe. Research is also observation and taking notes. Compare notes with you classmates.

Observe how the fringes on the screen change.

Questions :

- Is the central part becoming alternatively dark and bright? If yes, why?
- What are the timescales of these changes?
- What do you think is the reason for the changes in brightness?

Perform investigation

Now let's interact with the instrument in order to investigate and understand its behaviour. Don't forget to always take notes of your observations.

You can give a little push to one part of the instrument, or blow air in one of the two arms (be careful with your eyes!). What effect do these actions produce on the interference pattern?

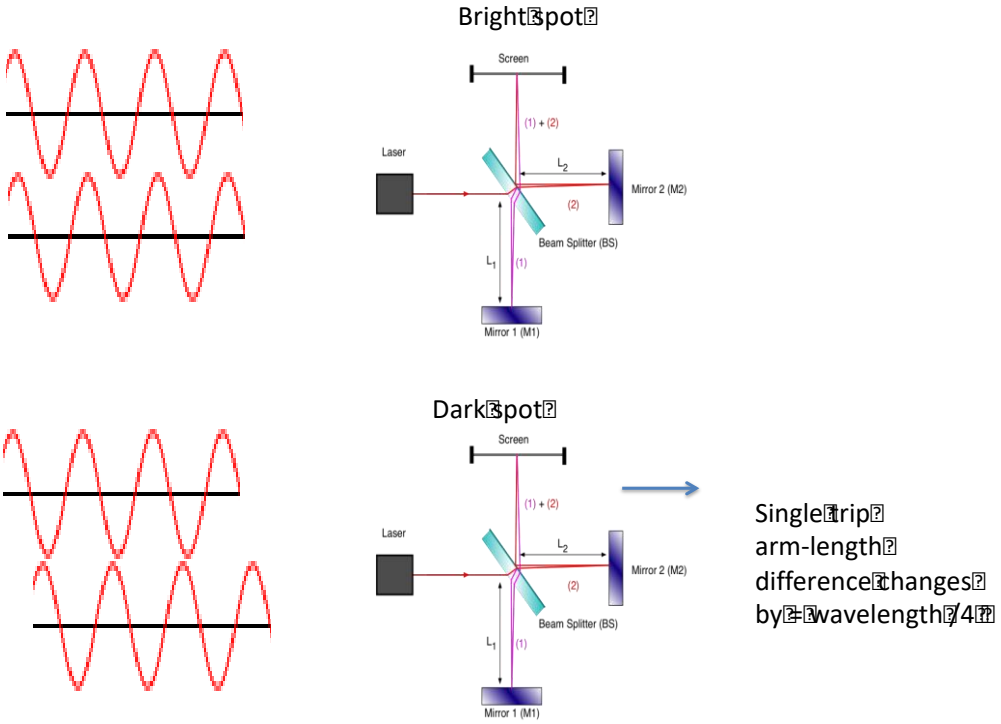
Try to study the characteristics of the fringes and identify those that you find more relevant.

Analysis and Interpretation: Gather result from data

Starting to appreciate the incredible precision of the interferometry

From previous observations you should appreciate how much the setup vibrates. To do that you need only to remark that the distance between to maxima of the is equal to the light wavelength, in our case ~ 0.6 micrometers (red light).

If the central spot changes from light to dark, the roundtrip distance difference between the two arms changes by half of 0.3 micrometers = 0.15 micrometers. This means that the single trip difference changes by 0.2 micrometers. See the figure



Question:

- How does this number compare with the size of an atom?
- How can we build a more stable interferometer?

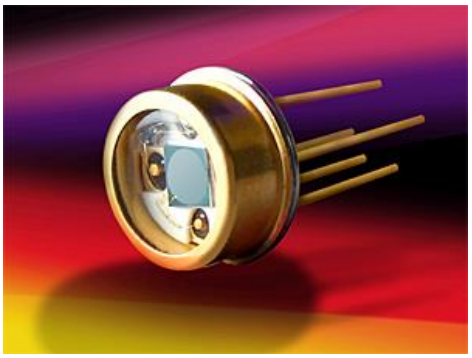
Test your hypothesis on the instrument.

- Try to explain why the instrument is so sensitive

- Which is the advantage of having a laser light, instead of having a normal light? Which is the property of the laser light, with respect of the standard light?

Increasing the sensitivity: photodetectors

Today we are measuring the change in optical power at the screen with a photodetector, a device which converts the optical power in an electrical current, which, in turn, can easily be converted in a change of voltage.



The limitation of this kind of measurement is due to the quantum nature of light, the fact that light is not only a wave, but also a particle. This generates an unavoidable fluctuation at the output of the photodetector called « shot noise ». However, by increasing the power of the laser, it is possible do reduce the impact of the shot noise. In Virgo and LIGO it is possible to measure a fraction of the wavelength equal to 10^{-12} (a millionth of a millionth).

Conclusion & evaluation

Conclude and communicate result/explanation

Exercise1:

Try to answer to the following questions (in a few lines)

How does a Michelson interferometer work?

Which is the difference between a wave and a particle?

Why have we used a laser in our experiment, instead of the light emitted by a lamp? Which is the difference between a laser and the light of a lamp?

Is it possible to make interference with radio waves rather than visible light? Why is it so?

Why is interferometry so powerful in measuring distances?

Are there alternative methods to measure distances very precisely?

Any ideas on how to remove the vibrations observed in the Nikhef interferometers?

Exercise 2

Search for material on the internet about the Michelson-Morley experiment and make a 5 minutes talk about this topic.

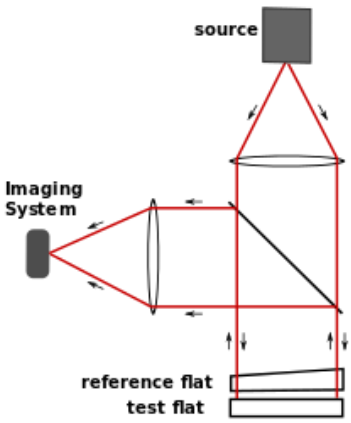
Evaluation/reflection

We have seen that the optical interferometry is a very powerful way to measure small distance differences.

The Michelson interferometer is not the only optical setup using interferometry. Let's analyse two other types of interferometers with experimental arrangements.

The fizeau interferometer

Interferometer are also a very powerful way to measure the shape or flatness of a surface, as in the optical system shown in the figure below, the « fizeau »interferometer.



In this setup, the two interfering beams are given: 1) from the reflected beam from a reference surface, 2) from the reflected beam by the test surface, after transmission by the reference surface.

See for example the web page here:

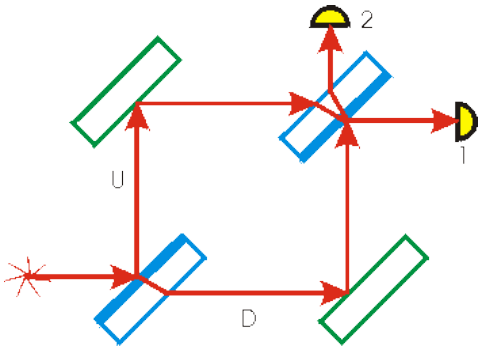
https://www.zygo.com/?/met/interferometers/verifire/

And the corresponding tutorial here:

https://www.youtube.com/watch?v=5r79RAoZsCM

The mach-zender interferometer

The Mach-Zender interferometer is shown is the following figure



In this setup the light is split in two parts with the beam-splitter (as in the Michelson) but they are not recombined at the same beam-splitter.

The Mach-Zender interferometer is widely used in quantum mechanical experiments. Take a look to this video:

https://www.youtube.com/watch?v=os4rDtjrP4c

The Mach-Zender interferometer can be also used to precisely stabilize the power at the port 1 or 2. Since the amplitude of the light depends on the interference between the two paths, one can move the position of one of the green mirrors to microscopically change the path and control precisely the output power.

A striking application of the Michelson interferometer:

Gravitational waves detection

The gravitational-wave detection was performed with giant Michelson interferometers, such as Virgo and LIGO. In the following picture we recognize the two arms.

The Virgo interferometer: we can appreciate the L shape of the Michelson interferometer

The central building hosts the laser, the beam-splitter and the output of the detector. In this case the change of optical length between the two arms is due to a gravitational-wave, a small ripple of the space-time, and it is measured using a photodetector.

Virgo and LIGO are, in fact, much more complex than a simple Michelson interferometer, but the basic principle is the same of the small prototype you built.

In the following video you can appreciate the complexity of the optics of the LIGO interferometer: https://vimeo.com/338761669

You can notice a flashing beam in one of the screens: this is the interference between the two arms, and the change in intensity of that beam, measured with a photodetector, contains the gravitational-wave signal.