A Brief Introduction to Interferometry

This document cannot begin to cover the whole field of optical interferometry, but it does describe what you can do in a first, hands-on, encounter with the construction, alignment, and use of an interferometer. It's meant to empower you, in teaching you that an interferometer is something you can understand from first principles, and build from scratch on an empty table.

Of all the experiments that demonstrate the interference of light, the Michelson interferometer is the most famous, due to its historical connection with 'ether-drift' experiments and the historical foundations of relativity. This kind of interferometer is also one of the easiest to set up and align, and it's also suited to a variety of amazingly sensitive measurements.

Lots of people have seen a stylized diagram of a Michelson interferometer; there's a crucial optical component labeled beamsplitter B (a.k.a. a 'half-silvered mirror', nowadays a dielectric layer deposited on a glass substrate, giving 50% transmission and 50% reflection). Light from a source S reaches this beamsplitter, and forms two beams that go to plane mirrors M₁ and M₂; those beams come back to the beamsplitter and head (in part) toward a detector D.

If we use $L_1$ and $L_2$ to denote the one-way lengths of the two arms, and use $\lambda$ for the wavelength of the light, then it's easy to show, in a simple model, that the intensity of light at detector D ought to behave as

$$I(\text{at D}) = \left(\frac{I_{\text{max}}}{2}\right) \left[1 + \cos \left(\frac{2 \pi (L_1 - L_2)}{\lambda/2}\right)\right].$$

That is to say, if arms lengths $L_1$ and $L_2$ are equal (or, if they differ by an integer multiple of $\lambda/2$), then the cosine factor is 1, and the intensity of light at the detector reaches a maximum, $I_{\text{max}}$. That's because under these conditions, the round-trip distances $2L_1$ and $2L_2$ will differ by an integer number of wavelengths, and the two beams rejoining at the
beamsplitter will meet in the in-phase condition. But if the two arm lengths mis-match, even by a single quarter-wavelength, then the intensity at the detector point drops all the way to zero.

For an interferometer illuminated by red light, $\lambda \approx 600$ nm, so a trifling motion of either mirror by a quarter-wavelength, $\lambda/4 \approx 150$ nm = 0.150 $\mu$m = 0.00015 mm = 1.5 x $10^{-7}$ m, turns an easily observed light intensity from maximum down to zero. This illustrates 'interferometric sensitivity', and it illustrates how sensitive to displacements (deliberate or inadvertent) an interferometer can be. And if a 150-nm displacement gives a 'full-scale' change in intensity, much smaller displacements will still give detectable signals.

But what does it take to translate this paper diagram into working table-top reality? Here are some issues you'll encounter.

A) The light source needs to be 'coherent'; really, that means 'coherent enough'. The more different the arm lengths $L_1$ and $L_2$ are, the more stringent this requirement; conversely, if $L_1$ and $L_2$ are equal to better than 1 $\mu$m, even white light can be used in the interferometer. Everyone's favorite first light source is a red helium-neon laser, operating at $\lambda = 633$ nm = 0.633 $\mu$m, and it is coherent enough (i.e. its optical frequency, near 473,000 GHz, is well-defined to better than 1 GHz) that arm length differences of an inch or two (2 - 5 cm) can be tolerated.

B) The interferometer needs to be aligned, so that the light beams really do take on the paths indicated in the figure. In particular, for interference to be visible, the beams returning from mirrors $M_1$ and $M_2$ need to encounter the beamsplitter so that they head toward the detector overlapping in position, and parallel in direction,. The art of building an interferometer is to include just enough mechanical adjustments to make this alignment possible, but to ensure that everything else stays fixed and rigid. You'll see how this is done in the TeachSpin interferometer. You'll also see the handsome 'fringes' that result from deliberate slight mis-alignment of the interferometer.

C) The interferometer needs to be mechanically stable. If you build it with arms $L_1$ and $L_2$ a foot long, then $L_1 \approx L_2 = 0.30$ m. Any change in dimensions $L_1$ or $L_2$, fast or slow, so big as $\lambda/4 = 0.15$ $\mu$m will change an interference maximum to a minimum -- and that change represents just half of a part-per-million change in the arm lengths! There are lots of influences, including small temperature changes, mechanical stresses, air-pressure fluctuations, and room vibrations, that can cause such tiny changes.

D) The 'detector' can be as simple as eyeball sighting of light on a screen, but it's much better to have an electronic photodetector. That gives the capability of fast response (0.1 ms is easily achieved), and a quantitative and linear response to the intensity at detector D. It also allows the interference signals to be displayed on an oscilloscope or captured by a computer.
Finally, here's just one of the uses of a Michelson interferometer: to measure $\lambda$ directly using ordinary tools. Suppose we have a way to move mirror $M_1$, by carefully controlled amounts -- we want it to move parallel to itself, by tiny yet measurable amounts. You'll see how the TeachSpin interferometer achieves this using a 'flexure translation stage', driven by a differential micrometer. Now every time this is used to move mirror $M_1$ by $\lambda/2$, there's an extra round-trip distance $\lambda$ that's been added to the light in arm #1. That one wavelength of extra distance (or equivalently, that time delay of one period of the optical oscillation) is enough to give one full cycle (say, from $I_{\text{max}}$ down to 0 and back up to $I_{\text{max}}$ again) in the intensity at detector $D$. So if you achieve a motion that allows you to count 100 such cycles of intensity variation, then you know you have moved the mirror by an amount that's equal to 50 $\lambda$. If you can also measure that distance in ordinary length units, using the micrometer, then you can write

$$50 \lambda = \text{the distance you measure on the 'diff mike'}$$

and solve for the wavelength $\lambda$, measured in ordinary units.

But there are other ways to configure an interferometer. In the Sagnac topology, shown below, a beamsplitter divides an entering laser beam into two emerging beams which transverse the periphery of a rectangular geometry in opposite directions.

![Sagnac interferometer layout](image)

A basic layout for a Sagnac interferometer (not to scale).
The two beams recombine back at the beamsplitter. The interferometer responds to the difference of phase accumulation of the beams traversing the circumference in clockwise and anti-clockwise directions. Since both beams are reflected by the same set of surfaces and components, most vibrational noise becomes a common-mode effect, to which the interferometer is insensitive.

Depending on the experimental set up, the counter propagating beams of the interferometer can either overlap or be separated in space. One application of adjacent but non-overlapping beams is to let one of the beams pass through a gas cell. Now a variation of gas pressure in the cell causes phase changes in the interferometer, and hence in its output signal. Using a differential pressure transducer allows quantitative and very sensitive detecting of the index of refraction of gases.
Modern Interferometry Workshop Abstract
Topical Conference on Advanced Labs
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The 'Modern Interferometry' set-up available from TeachSpin offers a tabletop-sized optical breadboard, and all the components required for students to lay out, build, and apply a variety of interferometer topologies. In the Workshop, participants will be guided through the actual assembly, alignment, and use of one such topology -- the Michelson interferometer.

Participants will see, at level A, Introduction to Interferometry

- an optical table with laser and alignment system installed
- how to lay out, assemble, and align a Michelson interferometer
- how to detect 'fringe formation' visually, and how to optimize alignment
- how to understand 'interferometric sensitivity', and its implications for vibrational effects
- how to add a photodetector, for the high-speed detection of signal variation

Participants will see, at level B, Applications of Interferometry

- how to make controlled and measurable sub-micron displacements of one mirror in the interferometer
- how to process fringe signals electronically, and how to 'count fringes', in order to measure the wavelength of light directly with a micrometer.
- how to derive an experimentally-measured value of the wavelength of light
- how to rearrange the optical layout to create an interferometer in the Sagnac configuration.