PRACTICUM III

Fundamental Basics of Modern Technologies

Practical #1

Fiber-Optics Interferometry

1. Introduction

Interferometers

An interferometer is an optical device which utilizes the effect of interference. Typically, it is based on the following operation principle: it starts with some input beam, splits it into two separate beams with some kind of beam splitter (a partially transmissive mirror), possibly exposes some of these beams to some external influences (e.g. some length changes or refractive index changes in a transparent medium), and recombines the beams on another beam splitter. The power or the spatial shape of the resulting beam can then be used e.g. for a measurement.

Interferometers frequently need to be made from high quality optical elements. For example, one often uses optical flats with a high degree of surface flatness.

Types of Interferometers

Mach–Zehnder Interferometer

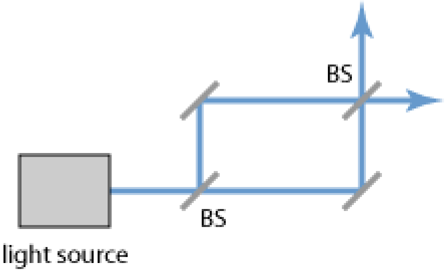

Figure 1: Mach–Zehnder interferometer.

The Mach–Zehnder interferometer was developed by the physicists Ludwig Mach and Ludwig Zehnder. As shown in Figure 1, it uses two separate beam splitters (BS) to split and recombine the beams, and has two outputs, which can e.g. be sent to photodetectors. The optical path lengths in the two arms may be nearly identical (as in the figure), or may be different (e.g. with an extra delay line). The distribution of optical powers at the two outputs depends on the precise difference in optical arm lengths and on the wavelength (or optical frequency).

If the interferometer is well aligned, the path length difference can be adjusted (e.g. by slightly moving one of the mirrors) so that for a particular optical frequency the total power goes into one of the outputs. For misaligned beams (e.g. with one mirror being slightly tilted), there will be some fringe patterns in both outputs, and variations of the path length difference affect mainly the shapes of these interference patterns, whereas the distribution of total powers on the outputs may not change very much.

Michelson Interferometer

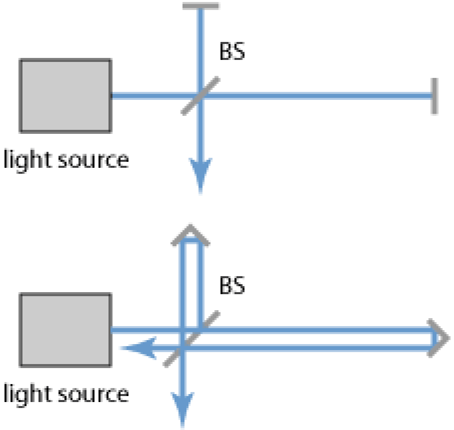

Figure 2: Michelson interferometers.

A Michelson interferometer, as invented by Albert Abraham Michelson, uses a single beam splitter for separating and recombining the beams. If the two mirrors are aligned for exact perpendicular incidence (see the upper figure), only one output is accessible, and the light of the other output goes back to the light source. If that optical feedback is unwanted (as is often the case with a laser, which might be destabilized), and/or access to the second output is required, the recombination of beams can occur at a somewhat different location on the beam splitter. One possibility is to use retroreflectors, as shown in the lower figure; this also has the advantage that the interferometer is fairly insensitive to slight misalignment of the retroreflectors. Alternatively, simple mirrors at slightly non-normal incidence can be used.

If the path length difference is non-zero, as shown in both parts of the figure, constructive or destructive interference e.g. for the downward-directed output can be achieved only within a finite optical bandwidth. Michelson originally used a broadband light source in the famous Michelson–Morley experiment, so that he had to build an interferometer with close to zero arm length difference.

There are many variations of the Michelson interferometer. For example, a Twyman–Green interferometer is essentially a Michelson interferometer with expanded beams in its arms. It is used for characterizing optical elements.

For more details, see the articles on Michelson interferometers and Twyman–Green interferometers.

Fabry–Pérot Interferometer

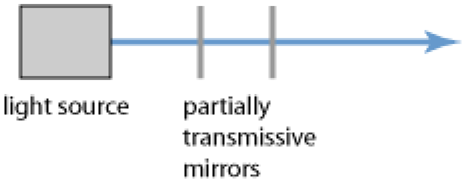

Figure 3: Fabry–Pérot interferometer.

A Fabry–Pérot interferometer (Figure 3) consists of two parallel mirrors, allowing for multiple round trips of light. (A monolithic version of this can be a glass plate with reflective coatings on both sides.) For high mirror reflectivities, such a device can have very sharp resonances (a high finesse), i.e. exhibit a high transmission only for optical frequencies which closely match certain values. Based on these sharp features, distances (or changes of distances) can be measured with a resolution far better than the wavelength. Similarly, resonance frequencies can be defined very precisely.

A modified version is the Fizeau interferometer, which is used for characterizing optical surfaces.

Another special kind of Fabry–Pérot interferometer, used for dispersion compensation, is the Gires–Tournois interferometer.

For more details, see the articles on Fabry–Pérot interferometers.

Sagnac Interferometer

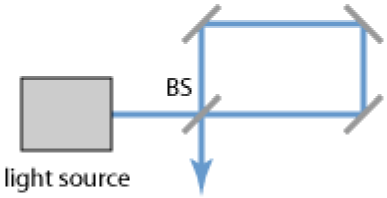

Figure 4: Sagnac interferometer.

A Sagnac interferometer (named after the French physicist Georges Sagnac) uses counterpropagating beams in a ring path, realized e.g. with multiple mirrors (as in Figure 4) or with an optical fiber. If the whole interferometer is rotated e.g. around an axis which is perpendicular to the drawing plane, this introduces a relative phase shift of the counterpropagating beams (Sagnac effect). The sensitivity for rotations depends on the area covered by the ring, multiplied by the number of round trips (which can be large e.g. when using many turns in an optical fiber). It is possible e.g. to obtain a sensitivity which is sufficient for measuring the rotation of the Earth around its axis.

Sagnac interferometers are used e.g. in inertial guidance systems.

Common-path Interferometers

Common-path interferometers use a common beam path but e.g. different polarization states for the two beams. This has the advantage that fluctuations of the geometric path length do not affect the interferometer output, whereas the interferometer can be a sensitive detector for birefringence. The Sagnac interferometer (see above) is another example; here, the interfering beams have opposite propagation directions.

Physical Principles of Interferometers

There are also substantially different principles of using interferometers. For example, Michelson interferometers are used in very different ways, using different types of light sources and photodetectors:

- When a light source with low optical bandwidth is used (perhaps even a single-frequency laser), the detector signal varies periodically when the difference in arm lengths is changed. Such a signal makes it possible to do measurements with a depth resolution well below the wavelength, but there is an ambiguity. For example, a monotonic increase or decrease of the arm length difference leads to the same variation of the detected signal. This problem may be solved by modulating the arm length difference e.g. with a vibrating mirror (or with an optical modulator) and by monitoring the resulting modulation on the detector in addition to the average signal power. Simultaneous operation of an interferometer with two wavelengths is another way of removing the ambiguity.
- If the detector is a kind of camera (e.g. a CCD chip) and the surfaces monitored are fairly smooth, the phase profile (and thus the profile of optical path length) can be reconstructed by recording several images with different overall phase shifts (phase-shifting interferometry). A phase-unwrapping algorithm can be used to retrieve unambiguously surface maps extending over more than a wavelength. However, such methods may not work for rough surfaces or for surfaces with steep steps.
- A white light interferometer uses a broadband light source (e.g., a superluminescent diode), so that interference fringes are observed only in a narrow range around the point of zero arm length difference. In that way, the above-mentioned ambiguity is effectively removed.

- A wavelength-tunable laser can be used to record the detector signal for different optical frequencies. From such signals, the arm length difference can be unambiguously retrieved. This works also with two-dimensional detectors (e.g. CCD cameras).
- If one of the mirrors is intentionally tilted, an interference fringe pattern is obtained. Any change in arm length difference will then move the fringe pattern. This method makes it possible to measure phase changes sensitively and also to measure position-dependent phase changes, e.g. in some optical element.

Another class of interferometric methods is named spectral phase interferometry. Here, interference in the spectral domain is exploited. The spectral modulation period is essentially determined by a time delay.

Applications

Interferometers can be used for many different purposes – by far not only for length measurements. Some examples are:

In 2016 it has been announced that a large interferometer operated at LIGO Hanford has detected gravitational waves resulting from the inspiral of two large black holes. An extraordinarily high detection sensitivity had to be achieved for that.

- for the measurement of a distance (or changes of a distance or a position, i.e., a displacement) with an accuracy of better than an optical wavelength (in extreme cases, e.g. for gravitational wave detection, with a sensitivity many orders of magnitude below the wavelength)
- for measuring the wavelength e.g. of a laser beam (→ wavemeter), or for analyzing a beam in terms of wavelength components
- for monitoring slight changes in an optical wavelength or frequency (typically using the transmission curve of a Fabry–Pérot interferometer) (frequency discriminators)
- for measuring rotations (with a Sagnac interferometer)
- for measuring slight deviations of an optical surface from perfect flatness (or from some other shape)
- for measuring the linewidth of a laser (→ self-heterodyne linewidth measurement, frequency discriminator)
- for revealing tiny refractive index variations or induced index changes in a transparent medium
- for modulating the power or phase of a laser beam, e.g. with a Mach–Zehnder modulator in an optical fiber communication system
- for measurements of the chromatic dispersion of optical components
- as an optical filter
- for the full characterization of ultrashort pulses via spectral phase interferometry

Depending on the application, the demands on the light source in an interferometer can be very different. In many cases, a spectrally very pure source, e.g. a single-frequency laser is required. Sometimes, the laser has to be wavelength-tunable. In other cases (e.g. for dispersion measurements with white light interferometers), a light source with a very broad and smooth optical spectrum is required.

Noise Influences

Interferometric measurements can be subject to laser noise, but often also from quantum noise influences. Typically, vacuum noise entering the open input port at a beamsplitter defines the standard quantum limit (shot noise limit) for the sensitivity [2, 5]. A noise level below that limit can be achieved by injecting squeezed states of light into an interferometer [2, 4, 12].

Fiber Interferometers

All the interferometer types discussed above can also be implemented with optical fibers. Instead of beam splitters, one then uses fiber couplers.

A potential difficulty is that the polarization state of light may change during propagation in the fiber. This often requires one to include a fiber polarization controller (which may occasionally have to be readjusted) or to use polarization-maintaining fibers.

Also note that temperature changes in the fibers (as well as bending) can affect the optical phase shifts. This can be a problem if different fibers belong to different interferometer arms. However, there are also fiber interferometers where one fiber serves for both arms, e.g. using two different polarization directions in the same fiber.

Birefringence in Nominally Symmetric Fibers

In principle, a fiber with a fully rotationally symmetric design should have no birefringence. It should thus fully preserve the polarization of light. In reality, however, some amount of birefringence always results from imperfections of the fiber (e.g., a slight ellipticity of the fiber core), or from bending. Therefore, the polarization state of light is changed within a relatively short length of fiber – sometimes only within a few meters, sometimes much faster.

Note that the index difference between polarization directions is not necessarily larger in fibers than in other devices. However, fibers tend to be long, so that even weak index differences can have substantial effects.

Another important aspect is that the resulting polarization changes are not only random and unpredictable, but also strongly dependent on the wavelength, the fiber's temperatures along its whole length, and on any bending of the fiber. Therefore, it often doesn't help that much to adjust a polarization state, e.g. using a fiber polarization controller (see below); some slight changes of environmental parameters or wavelength may again spoil the polarization.

Fiber Polarization Controllers

Strong bending of a fiber introduces birefringence. This means that some appropriate length of fiber, bent with a certain radius and fixed on a coil, can have a relative phase delay of π, or $\pi/2$, for example, between the two polarization directions. It can thus act like a $\lambda/2$ waveplate (half-waveplate) or a $\lambda/4$ waveplate (quarter-waveplate). If one rotates the whole coil around an axis which coincides with the incoming and outgoing fiber, one obtains a similar effect as for rotating a bulk waveplate in a free-space laser beam. One often uses a combination of an effective quarter-waveplate coil with a half-waveplate coil and another quarter-waveplate coil in series to transform some input polarization state into any wanted polarization state. Such a fiber polarization controller (Figure 1) can work over some substantial wavelength region.

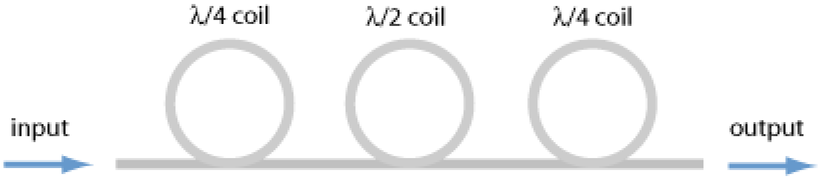

Figure 1: A “bat ear” polarization controller, containing three fiber coils which can be rotated around the input fiber's axis.

As mentioned before, the problem may remain that the input polarization state drifts with changing environmental conditions, so that the fiber polarization controller would have to be realigned frequently in order to preserve a constant output polarization state.

Polarization-maintaining Fibers

Fibers can be made polarization-maintaining (PM fiber) – but not by avoiding any birefringence! To the contrary, one intentionally introduces a significant birefringence. Such fibers are thus high-birefringence fibers (HIBI fibers).

There are essentially two common ways for doing that:

- A fiber can be made with an elliptical core. This results in some level of form birefringence. Of course, the fiber modes will also be affected by the elliptical shape, and the efficiency of coupling light to or from fibers with circular core is somewhat reduced.
- Some mechanical stress can be applied, e.g. by introducing stress rods made from a different glass. See Figure 2 for some typical realizations.

Figure 2: Polarization-maintaining PANDA fiber (left) and bow-tie fiber (right). The built-in stress elements, made from a different type of glass, are shown with a darker gray tone.

Note: a polarization-maintaining fiber does not preserve any polarization state of injected light! It does so only for linearly polarized light, where the polarization direction must be one of two orthogonal directions, e.g. along a line between the stress rods or perpendicular to it. The β value for some wavelength will significantly depend on that polarization direction.

What happens if we inject monochromatic with some other linear polarization direction? That can be considered as a superposition of the two basic polarization states. After a short length of propagation, these components will have acquired significantly different phase delays (due to their different β values). Therefore, they will no longer combine to the original linear polarization state, but rather in general to some elliptical state. After integer multiples of the polarization beat length, however, one again obtains a linear polarization.

Particularly for non-monochromatic light, a “polarization-maintaining” fiber does about the opposite of preserving the polarization state!

For non-monochromatic light, the situation becomes even more complicated. Over some length of fiber, the different wavelength components will experience different polarization-dependent phase shifts, so that the resulting polarization state becomes wavelength-dependent. To convert that back into a linear state would be difficult task – a simple polarization controller could not do that.

The need to align the input polarization state to a fiber axis in order to have the polarization preserved is of course a serious practical disadvantage of PM fibers. It requires more work to fabricate PM fiber-optic setups, for which additional equipment is required. Also, not all fiber components are available as PM versions. On the other hand, detrimental effects of drifting polarization states, which may otherwise require other measures, are safely avoided with PM setups.

Note that the introduced birefringence essentially removes any effect of some small additional random birefringence, as can result from moderate bending, for example. Such random influences may only very slightly change the local polarization, but will normally not have any significant effect on longer lengths. One can understand this by considering mode coupling: significant mode coupling requires a perturbation which has a period equal to the beat period of the two polarization states. For strong birefringence, that beat period (the polarization beat length) is rather short (for example, a few millimeters), and the usual perturbations are spatially too "slow" to cause any significant coupling, or at least do not have a strong spatial Fourier component according to the polarization beat.

Polarization-insensitive Designs

Often it is better to design systems such that polarization does not matter.

Another way of eliminating polarization issues is to design devices such that polarization does not matter. This approach is usually taken in optical fiber communications, for example. One simply takes care that no components are used which could cause substantial polarization-dependent losses, or which would rely on a certain polarization state. For example, one generally cannot use electro-optic modulators, and needs to carefully design any semiconductor devices for low polarization dependence. Some polarization effects still remain, which may limit the performance of very fast fiber-optic links. In particular, there is the phenomenon of polarization mode dispersion (PMD), which may be quantified as a differential group delay (DGD): signal components with different polarization may require slightly different times for traveling through a fiber cable, and that may deteriorate the signal quality. For short transmission distances and/or moderate bit rates, however, PMD is not a big issue.

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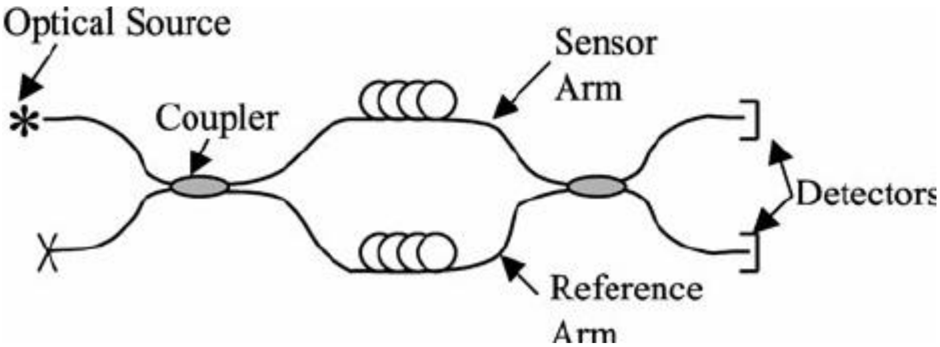
2. Experimental setup



3. Measurements and tasks

1. Identify PM and SM fibers
2. Assemble Mach-Zehnder interferometer
3. Measure the interference visibility
4. Estimate the sensitivity of the interferometer
5. …
6. ...

4. Questions

1. Coherence
2. Interference
3. Monochromatic light
4. Interferometers
5. Intensity of light
6. Optical fibers
7. Optical fiber elements
8. Optical fiber interferometer
9. Visibility
10. Sensitivity
11. Quantum noise
12. …
13. …
14. ...