Signal Detection in Interferometric Sensors

Week
VII

So far, we discussed interferometers from the perspective of working principles and took for granted the detection part: we consider the ideal case where we use a simple square-law detector and that we are able to obtain an intensity related to the phase and ultimately to our target quantity. Yet, in real-world conditions, detection can be more critical than the interferometer design itself, as assuring the detection of a good signal with meaningful information is a step of uttermost importance. This requires exploring possible problems and challenges of the configuration used, characteristics of the equipment, and also noise.

Table 5. Contents for Week VII

In general terms, when we think about signal detection in the context of optical interferometric sensors we are referring to the process of translating the phase information into a usable electrical signal. Referring to ideal characteristics of our detection scheme, we want to have an **accurate and stable output signal**, a **large Dynamic range**, and possibly a **large signal-to-noise ratio**.

Detection may be divided into **passive** or **active** schemes, depending if they require feedback of some information and signal back to the components of the interferometer, including to the sensor, to the laser source, or to other optical element. Currently, there are many detection schemes depending on the application and performance required. For the sake of simplicity, we will focus on three specific configurations which we will discuss in detail during this class: *homodyne*, *heterodyne*, and *pseudo-heterodyne* detection.

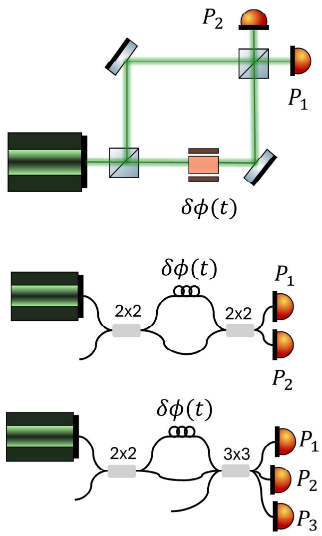

Figure 63. Passive Homodyne detection.

1 Homodyne detection

As we saw in the last few weeks, a standard two wave interferometer usually leads to intensities at the output ports given by the formula

$$I = \frac{1}{2}\left(I_0 + I_0 \cos(\Delta\phi)\right) \tag{1.1}$$

where $\Delta\phi$ is the phase difference of the two optical beams that ultimately is related to what we want to measure. For the present chapter, we will consider this phase difference to be composed as

$$\Delta\phi = \phi_0 + \delta\phi(t), \tag{1.2}$$

i.e. a static or quasi-static phase difference ϕ_0 related to the configuration of the interferometer plus a time-varying signal $\delta\phi(t)$ which corresponds to the signal we want to detect. Substituted into equation 1.1 it gives

$$I = \frac{I_0}{2} + \frac{I_0}{2}\cos(\phi_0 + \delta\phi(t)), \tag{1.3}$$

being straightforward to conclude that inverting the relation between measured I to obtain $\delta\phi(t)$ is highly nonlinear and non-trivial depending on factors such as the amplitude of $\delta\phi(t)$ and initial interferometer configuration. For small signal perturbations $\delta\phi(t) \ll 1$ it is possible to expand equation 1.3 to the first order terms as

$$I = \frac{I_0}{2} + \frac{I_0}{2}\cos(\phi_0) - \sin(\phi_0)\phi(t) + O(\delta\phi^2). \tag{1.4}$$

Looking at this formula two conclusions emerge, eventually related to the problems of homodyne detection:

- **Limited Dynamic Range**: The formula is only valid for small perturbations.
- **Varying Sensitivity**: depending on the phase ϕ_0 one can have maximum sensitivity (for $\phi_0 = (2m+1)\pi/2$) or even reach zero sensitivity ($\phi_0 = m\pi$). As this phase difference usually depends on the initial optical path difference, say OPL_0 but also on the wavelength itself, i.e. $\phi_0 = 2\pi OPL_0/\lambda$, the sensitivity may be strongly affected by **mechanical or laser variations and drifts** over time.

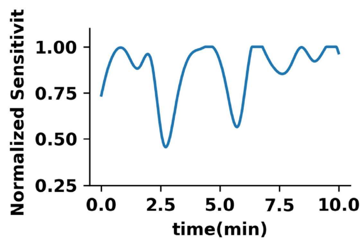

Figure 64. Typical temporal drift of the sensitivity in Passive Homodyne.

Combining the signals of two or more output ports and multiple wavelengths, one can work out numerical methodologies to circumvent the varying sensitivity problem(see examples in Figure 64). This can be done without dramatically changing the configuration nor requiring active elements operating on the system, yet their performance is typically less stable compared to active homodyne configurations.

1.1 Active Homodyne

To circumvent the instability of **passive homodyne** detection in terms of sensitivity one can employ **active** configurations by adding optical components for active phase tracking. The idea is to incorporate a component on the reference arm of the interferometer (e.g. a fiber stretcher or a piezo-electric

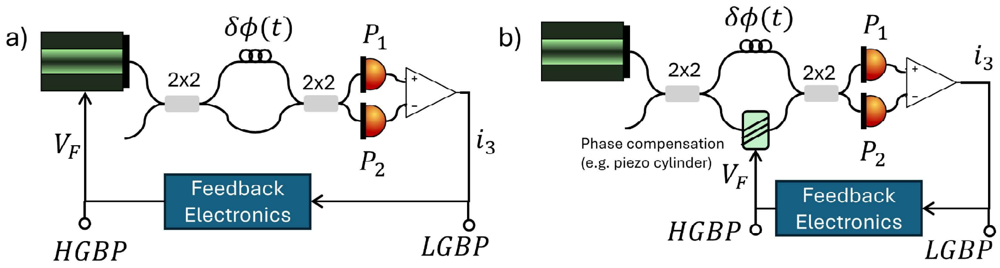

Figure 65. Active Homodyne Configurations.

controlled mirror) to maintain the interferometer on the point of maximum sensitivity, defined as **quadrature**,

$$\phi_0 - \phi_{act} = \frac{(2m+1)\pi}{2} \tag{1.5}$$

where m is an arbitrary integer number and ϕ_{act} is the phase introduced by the active element. In this case, it is typical to subtract the two ports of the interferometer[49] to get I_3 without a DC component as

[49] if possible

$$I_3 = I_0 \cos(\phi_0 + \delta\phi(t) - \phi_{act}). \tag{1.6}$$

Considering the schematic of Figure 65, the feedback signal following to the active element is $V = G \int I_3(t^{'})dt^{'}$ where G is a gain parameter, being straightforward to demonstrate that in the case of ϕ_{act} correcting to the quadrature point, the feedback loop follows the differential equation

$$\frac{dV}{dt} \approx I_0 G(\phi_0 + \delta\phi(t) - \phi_{act} - \pi/2) \tag{1.7}$$

or considering the introduced phase change to be proportional to an applied voltage as $\phi_{act} = kV$,

$$\frac{dV}{dt} + I_0 GkV = I_0 G(\phi_0 + \delta\phi(t) - \pi/2). \tag{1.8}$$

In this form, the term $I_0 Gk$ is usually called the gain-bandwidth product of the feedback circuit and establishes two regimes for operation:

- For frequencies of $\delta\phi(t)$ much smaller than the gain-bandwidth product, the derivative can be neglected and the term $\delta\phi(t)$ may be extracted by *reading and filtering the signal information of the feedback voltage* given by

$$kV = \phi_0 + \delta\phi(t) - \pi/2. \tag{1.9}$$

- For frequencies of $\delta\phi(t)$ larger than the gain-bandwidth product, the term $\delta\phi(t)$ needs to be extracted from the signal of I_3 and the correction only accounts for the drift term ϕ_0.

This detection scheme is easy to implement, provides a highly linear operation, and the noise introduced in the sensor is usually negligible. Yet, there are still drawbacks:

- **Limited Dynamic Range**: The amount of correction that you can get with a piezoelectric element is usually small, meaning that the dynamic range is still limited;
- **Piezoelectric Devices**: One of the disadvantages of piezoelectric devices is that they usually require high voltages (up to thousands of Volts), which can be detrimental for the versatility of the final solution (e.g. electric sensors).

A possible configuration to bypass the second problem is to act directly on the laser, using wavelength tuning. In particular, in the case of diode lasers, it is possible to modulate (in a typically small range) the emission frequency of the laser by $\Delta\nu = k_d \Delta i_L$ via the provided current change Δi_L. In this case, the phase difference generated will be $\phi_{act} = \frac{2\pi OPL_0}{c}\Delta\nu$ which can easily be worked out and solved for Δi for achieving the condition $\phi_0 - \phi_{act} = \frac{(2m+1)\pi}{2}$.

2 Heterodyne detection

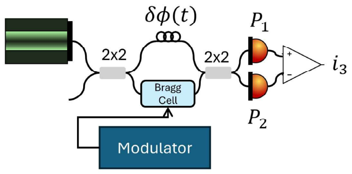

Figure 66. Heterodyne Detection.

In very generic terms heterodyne detection involves mixing a signal of interest with a reference signal, called the **local oscillator**, which has a slightly different oscillation frequency. Under this mixing process, new frequencies at the sum and difference of the original frequencies appear at the detection level[50]. For example, going back to the Mach-Zehnder interferometer configuration setup, we can add an optical component - called an acoustic-optic modulator or Bragg Cell (see Figure 67) - which is the first order of transmission provides a frequency shift to the original wave frequency

[50] These frequencies only appear due to the square-law detection, and are not related to the oscillatory field itself.

$$\omega_{LO} = \omega - \omega_{IF}. \tag{2.1}$$

In this case, it is straightforward to recover the interferometer formula as dependent on this frequency difference:

$$I_6(t) = \frac{I_s + I_{LO}}{2} - 2\sqrt{I_s I_{LO}}\cos(\omega_{IF}t + \phi_0 - \phi_{LO} + \delta\phi(t)) \tag{2.2}$$

whose DC term can again be eliminated in differential detection if we have access to a second port of the interferometer.

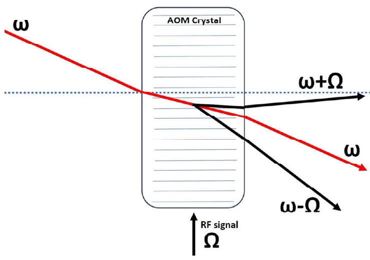

Figure 67. Bragg Cell working principle.

Typically, the frequency of interest in an interferometric setup is the one that is shifted to a more manageable frequency range for easier signal processing. In this context, the objective is to convert a high-frequency signal into a lower frequency that retains the amplitude and phase information of the original signal and thus the term to be considered is the difference term, i..e with frequency ω_{IF}. The demodulation of this signal can be experimentally done using a **Lock-in amplifier** or a **Phase-tracking circuit**.

The major advantages of heterodyne detection are:

- **Sensitivity and Selectivity**: Multiplied by the local oscillator amplitude, heterodyne detection allows higher sensitivity to small changes in phase even if the amplitude of the signal is very faint;

- **Robustness to noise and frequency translation**: While typical noise spans over a wide frequency range, the possibility of measuring signals at very specific frequencies makes it ideal to bypass the challenges of noisy environments;

- **Large Dynamic Range**: Conceptually, if interrogated properly, it may feature an infinite dynamic range.

In this line, one may be inclined to conclude that if possible, heterodyne detection is preferable. Yet, in practice, there are however also a few challenges:

- **Requirement of additional components**: in particular, a rather bulky acoustic-optic modulator, which introduces more complexity and has a large footprint incompatible with miniaturization and may increase the cost;

- **Complexity and Stability of frequency**: If not on the laser side (e.g. two frequency lasers), the setup for heterodyne detection is typically more complex than that for homodyne detection. It requires precise control of the local oscillator frequency and phase.

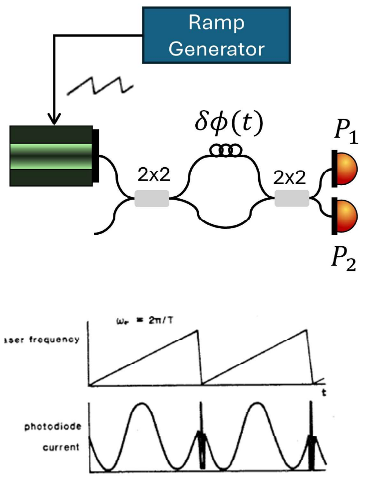

Figure 68. Typical Pseudo-Heterodyne Detection.

3 Pseudo-Heterodyne detection

As seen, heterodyne detection features interesting mathematical advantages, yet true heterodyne detection is highly limited in the experimental world by practical applications. The pseudo-heterodyne detection aims to circumvent these problems by modulating the laser source.

Considering the case of Figure 68, consisting of an interferometer with unbalanced arms with path difference L, it is trivial to demonstrate that a shift in the laser emission frequency $\Delta\nu$ leads to a phase shift

$$\phi_{act} = \frac{2\pi Ln}{c}\Delta\nu. \tag{3.1}$$

Again, in diode lasers, this can be achieved using a current modulation. It is trivial to demonstrate that if you modulate the laser with a ramp, it will act as an effective modulation frequency $\omega_m = \frac{2\pi Ln}{c}\frac{di}{dt}K_d(\omega)$ (see Figure 69). In this way, you can recover the same results that you would have if you measured it with true heterodyne.

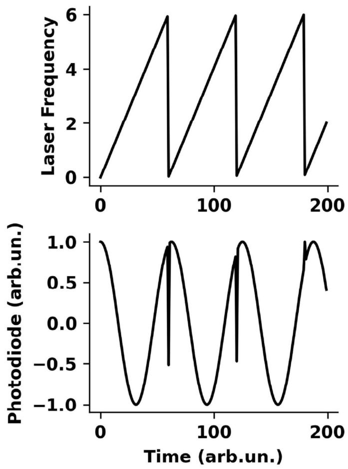

Figure 69. Ramp Modulation and resulting signal.

4 Concluding Remarks

During this chapter, we explored the intricacies of signal detection in interferometric sensors, focusing on the comparative advantages and challenges of homodyne and heterodyne detection methods. We have shown that while the most classical homodyne detection seems straightforward and cost-effective, it suffers from several practical limitations for supporting real-world sensing devices. If limitations for the final application, these drawbacks can be mitigated to some extent by using active homodyne, heterodyne, and pseudo-heterodyne detection schemes. Yet, the complexity of the setup and the need for additional components can also pose challenges, meaning that the ultimate choice between homodyne and heterodyne detection methods depends on the specific requirements of the application, as synthetized in the final Table 6.