Optical Heterodyne Detection Methods. Chem 243. R. Corn

Sources: https://www.rp-photonics.com/optical_heterodyne_detection.html
https://en.wikipedia.org/wiki/Optical_heterodyne_detection

Heterodyne detection (also called coherent detection) is a detection method which was originally developed in the field of radio waves and microwaves. There, a weak input signal is mixed with some strong "local oscillator" wave in some nonlinear device such as a rectifier, and the resulting mixing product is then detected, often after filtering out the original signal and the local oscillator frequency. The frequency of the mixing product is the sum or the difference of the frequencies of the signal and the local oscillator.

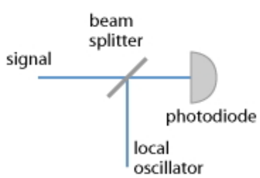

Figure 1: Setup for optical heterodyne detection.

Optical heterodyne detection involves optical signal and local oscillator waves, whereas the mixing product is an electrical signal. The mixing product is not obtained by mixing the signal and local oscillator wave in a nonlinear crystal, but rather simply by detecting the linearly superimposed waves with a square-law photodetector, typically a photodiode. For example, one uses a beam combiner (or beam splitter) as in Figure 1 and aligns the two beams such that they are mode-matched. This means not only that their intensity profiles overlap, but also that their wavefronts have the same curvature on the detector, so that the interference conditions are uniform over the full detector area. Of course, this is possible only if the two beams are spatially coherent. In a fiber-optic setup, a fiber coupler would be used instead of the beam splitter, and all fibers would be single-mode fibers, possibly of polarization-maintaining type; the mode matching is then guaranteed without a special alignment.

The resulting photocurrent is proportional to the total optical intensity, thus to the square of the total electric field amplitude. If the signal and local oscillator powers and frequencies are constant, the photocurrent has two different frequency components:

$$I \propto [E_{\text{sig}} \cos(\omega_{\text{sig}} t + \varphi) + E_{\text{LO}} \cos(\omega_{\text{LO}} t)]^2 \propto \frac{1}{2}E_{\text{sig}}^2 + \frac{1}{2}E_{\text{LO}}^2 + 2E_{\text{LO}}E_{\text{sig}} \cos(\omega_{\text{sig}} t + \varphi)\cos(\omega_{\text{LO}} t)$$

The constant (zero-frequency) part is proportional to the sum of local oscillator and signal power. The part oscillating with the sum and difference frequencies has an amplitude proportional to the product of the electric field amplitudes (not the optical powers) of signal and local oscillator.

$$\cos A \cos B = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$$

The oscillating part can then be isolated and processed further with electronic means. Its electric power is proportional to the product of the optical powers of signal and local oscillator. With a strong local oscillator, the heterodyne signal resulting from a weak input signal can be much more powerful than for direct detection. In that sense, heterodyne detection provides a signal gain, although there is no optical amplification involved.