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White Paper

Principles of lock-in detection and the state of the art

Last updated: April 2023

Introduction

Lock-in amplifiers were invented in the 1930s [1, 2, 3] and commercialized [4] in the mid 20th century as electrical instruments capable of extracting signals in pulsed and gated in extremely noisy environments (see Figure 1). They employ a synchronous detection scheme and low-pass filtering to measure a signal's amplitude and phase relative to a periodic reference. A lock-in measurement extracts signals in a defined frequency band and the reference frequency, effectively rejecting all other frequency components. The best instruments on the market today have a dynamic range of 100 dB [5], which means they are capable of accurately measuring a signal in the presence of noise up to a million times higher in amplitude than the signal of interest.

Over decades of development, researchers have found many different ways to use lock-in amplifiers. Most prominently they are used as precision AC voltage and AC phase meters, noise measurement units, impedance spectroscopies, network analyzers, spectrum analyzers and phase detectors in phase-locked loops. The fields of research comprise almost every length scale and temperature, such as the observation of the coexistence of full and dimerized [6], measuring the fractional quantum Hall effect [7], or direct imaging of the bond characteristics between atoms in a molecule [8]. Lock-in amplifiers are extremely versatile. As specialized spectrum analyzers and oscilloscopes, they are workhorses in all kinds of laboratory setups, from physics to engineering and life sciences. As with most powerful tools, only a solid understanding of the working principles and features enables the user to get the most out of it and to successfully design experiments.

This document provides a quick introduction to the principles of lock-in amplification and explains the most important measurement settings. The lock-in detection technique is described both in the time and in the frequency domain. Moreover, details are laid out on how signal modulation can be implemented in order

to improve on signal-to-noise ratio (SNR) while keeping acquisition time low. Finally, recent innovations are discussed and the state of the art is described.

Lock-in amplifier working principle

Lock-in amplifiers use the knowledge about a signal's time dependence to extract it from a noisy background. A lock-in amplifier performs a multiplication of its input with a reference signal, also sometimes called down-mixing or heterodyne/homodyne detection, and then applies an adjustable low-pass filter to the result. This method is termed demodulation or phase-sensitive detection and isolates the signal at the frequency of interest from all other frequency components. The reference signal is either generated by the lock-in amplifier itself or provided to the lock-in amplifier and the requirement for an external source. The reference signal is usually a sine wave but could have other forms, too. Demodulation with a pure sine wave enables selective measurement at the fundamental frequency or any of its harmonics. Some instruments use a square wave [9] which also captures all odd harmonics of the signal and, therefore, potentially introducing systematic measurement errors.

To understand lock-in detection, we will look at both

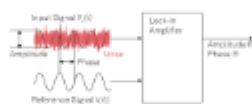


Figure 1. Lock-in amplifiers are capable of measuring the amplitude and the phase of signals relative to a stable reference signal, even if the signal is entirely buried in noise.



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Principles of Lock-in Detection

Explore the world of lock-in amplifiers in this paper, vital for success in photonics labs. Grasp the details of detecting amplitude and phase amid widespread signal changes from pulsed lasers, acousto- and electro-optic modulators, optical choppers, and other devices. Delve into essential measurement settings, and insights about detection techniques in the time and frequency domains and draw some inspiration from the latest developments for your own experimental challenges.

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