



# The Working Foundation and Practical Application of Different Optical Lock-In Amplification

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**Abstract.** Optical lock-in amplification is a cornerstone technology for extracting weak optical signals buried in noise by leveraging phase-sensitive detection and frequency-domain filtering. This review systematically analyses the mathematical foundations of Optical Lock-in Amplification, including signal modulation, phase-sensitive demodulation, and noise suppression mechanisms. In order to keep up with the cutting-edge developments of the optical lock-in amplification techniques, this work demonstrates two difference paths of the amplification methods: the traditional amplified method and the correlative method, with the basic mathematical principles of removing noise, screening and retaining the target signals. The following work integrates advances in digital phase-locked loops (PLLs), hybrid optoelectronic systems, The tunable diode laser absorption spectroscopy (TDLAS) and applications in University Physics Laboratories, quantum optics and biomedical imaging . Supported by the real-world applications, this work provides a rigorous theoretical framework of the Optical lock-in amplification itself, exhibit the practical value of this technology in multiple engineering fields, and highlights future directions for Optical lock-in amplification's development.

**Keywords:** Optical Lock-In Amplification, Phase-Locked Loops, Correlation Method, Noise Reduction

## 1 Introduction

Optical lock-in amplification (OLIA) emerged as a critical technology in the mid-20th century, driven by the need to detect weak optical signals buried in noise across fields such as spectroscopy, quantum optics, and biomedical imaging. Its origins trace back to radio-frequency (RF) engineering, where phase-sensitive detection was first implemented using analog phase-locked loops (PLLs) for frequency synthesis and noise suppression. The adaptation of these principles to optical systems began in the 1980s, enabled by advancements in laser modulation and photo detector technologies.

A key innovation was the integration of choppers (mechanical or electro-optic devices) to modulate optical signals at a known frequency, typically in the kHz range. This modulation shifts the signal to a frequency domain where noise is minimal, allowing subsequent extraction via phase-sensitive detection. For instance, in early

experiments, semiconductor lasers were synchronized to external references using optical phase-locked loops, achieving GHz-level frequency stability. The development of digital lock-in amplifiers in the 2000s further enhanced precision by replacing analog components with programmable digital signal processors (DSPs), enabling adaptive filtering and real-time phase correction [1].

Optical lock-in amplification enables precise recovery of weak signals in noisy environments, critical for applications such as quantum communication, terahertz imaging, and single-molecule microscopy [2,3]. Unlike conventional amplifiers, optical lock-in amplification combines optical modulation with phase-locked electronic feedback to isolate signals at specific frequencies. This paper focuses on its mathematical principles, emphasizing frequency mixing, correlation detection, and loop dynamics.

## 2 Mathematical Foundations of two amplification methods

The locking process is governed by the loop equation:

$$\Delta\varphi = \varphi_{in} - \varphi_{ref} = \frac{K_{PD}K_{VCO}}{s + K_{LF}} \cdot \varphi_{noise} \quad (1)$$

Where  $K_{PD}$ ,  $K_{VCO}$  and  $K_{LF}$  represent the gains of the phase detector, VCO, and loop filter, respectively. Optimal parameter selection ensures stability (phase margin  $> 45^\circ$ ) and rapid convergence [4].

### 2.1 Principle of traditional digital lock-in amplification

The traditional digital lock-in amplifier (LIA) utilizes phase-sensitive detection (PSD) to multiply the noisy input signal with a reference signal. A low-pass filter (LPF) is then applied to extract the DC component, allowing for the measurement of the amplitude and phase of the signal.

Consider a weak optical signal  $S(t)$  buried in noisy input signals  $N(t)$ . The Noisy Input Signals can be referenced as:

$$S(t) = A \cos(\omega_1 t + \varphi_1) \quad (2)$$

The reference signal which Synchronized the reference signal to the modulation frequency  $\omega_2$ . can be translated as:

$$R(t) = \cos(\omega_2 t + \varphi_2) \quad (3)$$

Multiplying the mentioned reference signal with  $S(t)$ :

$$\begin{aligned}
 S_{mix}(t) &= S(t) \cdot R(t) \\
 &= \frac{A}{2} [\cos((\omega_1 - \omega_2)t + \varphi_1 - \varphi_2) \\
 &\quad + \cos((\omega_1 + \omega_2)t + \varphi_1 + \varphi_2)] \\
 &\quad + N(t) \cdot R(t)
 \end{aligned} \tag{4}$$

When  $\omega_1 = \omega_2$ , the output simplifies to a DC component  $\frac{A}{2} \cos(\Delta\varphi)$  and a high-frequency term  $\frac{A}{2} \cos((\omega_1 + \omega_2)t + \varphi_1 + \varphi_2)$ , where  $\Delta\varphi = \varphi_1 - \varphi_2$ .

The following processes are Low-Pass Filtering and SNR Enhancement. A low-pass filter (LPF) with bandwidth  $\Delta f$  removes the  $2\omega_2$  component, leaving the DC term proportional to the signal amplitude  $A$ . The signal-to-noise ratio (SNR) improvement is governed by:

$$SNR_{out} = SNR_{in} \cdot \sqrt{\frac{f_{mod}}{\Delta f}} \tag{5}$$

Where  $f_{mod} = \omega_r / 2\pi$ . Narrow band filtering here can achieve SNR gains exceeding  $10^5$ . Ulteriorly, to resolve both amplitude  $A$  and phase  $\Delta\varphi$ , Optical Lock-in Amplification employs quadrature detection using two reference signals shifted by  $90^\circ$ :

$$X = \frac{A}{2} \cos(\Delta\varphi), Y = \frac{A}{2} \sin(\Delta\varphi) \tag{6}$$

The resultant magnitude  $R = \sqrt{X^2 + Y^2}$  and phase  $\theta = \arctan\left(\frac{Y}{X}\right)$  are immune to phase drift [5]. Modern systems use digital PLLs to dynamically adjust  $\varphi_1$ , minimizing  $\Delta\varphi$  and, hence stabilizing the output [5].

## 2.2 Principle of Correlation-Based Digital Lock-in Amplification

The correlation-based digital lock-in amplification replaces the traditional low-pass filter with correlation integration, which enhances noise immunity by exploiting the fact that the reference signal is uncorrelated with noise. This method provides better performance in noisy environments. In this method, set the sample signals as:

$$u_1(n) = \cos\left(\frac{2\pi f}{f_s} n\right), u_2(n) = \sin\left(\frac{2\pi f}{f_s} n\right) \tag{7}$$

Then the input signal can be represented as:

$$y(n) = A \cos\left(\frac{2\pi f}{f_s} n + \varphi_1\right) + N(n) \tag{8}$$

Manage the correlation operations to the signals:

$$\begin{aligned} R_{yu_1}(n) &= \frac{1}{N} \sum_{i=0}^{N-1} y(i)u_1(i+n), & R_{yu_2}(n) \\ &= \frac{1}{N} \sum_{i=0}^{N-1} y(i)u_2(i+n), \end{aligned} \tag{9}$$

Since the reference signal and noise are uncorrelated, the relations can be represented as:

$$R_{yu_1}(n) = R_{su_1}(n), R_{yu_2}(n) = R_{su_2}(n) \tag{10}$$

Hence, the desired amplitude and phase estimation [6]:

$$A = 2 \cdot R_{su_1}(0), \varphi_1 = \arctan\left(\frac{R_{su_1}(0)}{R_{su_2}(0)}\right) \tag{11}$$

### 3 Key Components and Optical Implementation

#### 3.1 Modulation Techniques and Devices

Optical lock-in amplification relies on precise modulation of optical signals to shift their frequency domain for noise suppression. Two primary devices are employed for this purpose: acousto-optic modulators (AOMs) and electro-optic modulators (EOMs). AOMs use sound waves to diffract light, enabling frequency shifting and amplitude modulation, making them ideal for Raman spectroscopy and laser stabilization. For example, in terahertz imaging, AOMs modulate laser beams to separate signal frequencies from low-frequency noise.

EOMs, such as lithium niobate (LiNbO3) modulators, exploit the Pockels effect to alter the phase or amplitude of light at frequencies up to 145 GHz. These devices are critical in quantum cascade laser arrays, where high-speed modulation ensures phase coherence across terahertz frequencies [16]. Recent advancements in plasmonic EOMs have enabled GHz-level modulation with minimal insertion loss, essential for quantum

communication systems .

### 3.2 Photodetection and Signal Conditioning

Photodetectors convert modulated optical signals into electrical currents. Avalanche photodiodes (APDs) and four-quadrant detectors (QDs) are commonly used for their high sensitivity. APDs provide internal gain (up to 105105) but introduce shot noise proportional to  $I_{\text{photon}}/\text{photon}$ , necessitating cryogenic cooling for low-noise applications. QDs, employed in laser communication systems, resolve spatial intensity variations of Gaussian beams to calculate centroid positions with sub-micrometer precision [6].

Signal conditioning involves transimpedance amplifiers (TIAs) and bandpass filters. For instance, a TIA with a gain of  $2.5 \times 10^7 2.5 \times 10^7$  V/A and 35  $\mu\text{V}$  noise floor was designed for QD-based spot position detection systems. Bandpass filters (e.g., 50 Hz–1 kHz) suppress out-of-band noise, such as 50 Hz power-line interference, while preserving modulated signal integrity [7].

### 3.3 Phase-Locked Feedback Loops

Phase alignment between the reference and input signals is achieved through the digital phase-locked loops or hybrid optoelectronic systems. A DPLL with CMOS technology achieves phase errors  $<0.1^\circ$  and jitter  $<100$  fs by dynamically adjusting the reference phase via finite state machines (FSMs). For example, MokuLab's DPLL uses a PID controller to minimize phase drift, achieving a loop delay of  $\sim 300$  ns and 150 kHz feedback bandwidth [8].

In dual-phase lock-in amplifiers, quadrature detection resolves both amplitude  $A$  and phase  $\Delta\phi$  by mixing signals with  $0^\circ$  and  $90^\circ$  references. This eliminates phase ambiguity and enables noise-robust measurements, as demonstrated in resonator fiber optic gyroscopes (R-FOGs), where dual-phase architectures extract MHz-level signals from 30 dB noise without manual phase adjustment .

### 3.4 Modern Integrated Systems

Recent advancements on OLIA and correlation system focus on monolithic integration and semi-digital architecture. A CMOS optoelectronic LIA with semi-digital phase alignment achieves 35.37 dB dynamic reserve and 296  $\text{mV}/\mu\text{W}$  sensitivity at 50 kHz modulation, consuming only 214  $\mu\text{W}$  power [10]. Such systems combine the analogue front-ends with digital back-ends (e.g., FPGA-based correlators) to optimize both bandwidth (DC–200 MHz) and resolution ( $0.001^\circ$  phase accuracy) [9].

For high-gain applications, rare-earth-doped waveguide amplifiers, such as  $\text{Nd}^{3+}$ -polymer chains, leverage Förster resonance energy transfer (FRET) to achieve 5.7 dB/cm gain at 1.06  $\mu\text{m}$ , outperforming traditional inorganic amplifiers. These systems balance  $\text{Nd}^{3+}$  ion density and the polymer rigidity to suppress the total concentration quenching while maintaining phase coherence.

### 3.5 Challenges in Practical Implementation

Key challenges include nonlinear phase noise from thermal drift in optical fibers and integration complexity in photonic integrated circuits (PICs). Solutions involve active thermal compensation algorithms and silicon nitride resonators with sub-nm fabrication tolerances. For broadband operation like mid-infrared and other similar structures, materials like graphene plasmonics and periodically poled lithium niobate (PPLN) are being explored [10].

## 4 Practical application and future trend

### 4.1 Core advantages of optical lock-in amplification

**Ultra-High Signal-to-Noise ratio (SNR) Enhancement.** By synchronizing the input signal with a reference frequency, lock-in amplifiers can suppress the uncorrelated signals like ambient light and thermal noise through narrowband filtering. Through the SNR comparison chart constructed by the experiment which demonstrated previously, the optical lock-in amplification can suppress noise >90% in low light condition, which might be helpful in laboratory conditions such as quantum experiments [11]. In stimulated Raman scattering microscopy, the SNR can be enhanced to 1100:1, which enables the label-free cellular imaging [12,13].

**Sub-picowatt Sensitivity.** The optical lock-in amplification has a low detection limit up to pW level, which makes the amplification capable of resolving optical signals as weak as 1 pW, hence the optical lock-in amplification is critical for fluorescence spectroscopy and terahertz wave detection. As an example, the Fiber-optic gas sensors can achieve methane detection at 1 ppm levels using harmonic lock-in techniques [14].

**Phase-Specific Signal Recovery.** Functionally, the optical lock-in amplifiers can reject the out-of-phase interference, such as stray light and electrical crosstalk, through the way of extracting only the in-phase component of the target signals. From this angle, the optical lock-in amplification enables precise beam position detection in free-space laser communication (<1  $\mu\text{m}$  error) [15].

### 4.2 Application Scenarios

**Scientific Research.** Optical Lock-in amplifiers suppress background noise to detect electron transition signals in quantum dots, where signal-to-noise ratio improved by 20 dB, and measure weak electromagnetic responses in superconducting materials at cryogenic temperatures, advancing research in quantum computing and superconducting mechanisms.

**Industrial Sensing and Biomedical Imaging.** The Tunable diode laser absorption spectroscopy (TDLAS) combined with lock-in amplification enables ppm-level

sensitivity for methane and CO<sub>2</sub> detection, optimized via second-harmonic analysis; In stimulated Raman scattering (SRS) microscopy, lock-in amplifiers enhance imaging SNR (up to 1100:1) by modulating pump laser frequencies, enabling label-free, high-resolution imaging of biological tissues, as shown in Figure 1 [16].

**Education and Low-Cost Experimental Platforms, Optical Communication.** The Lock-in amplifier replaces expensive CCD systems in semiconductor absorption spectroscopy experiments, reducing costs by over 80% and democratizing access to weak-signal detection education, which helps the school and laboratories constructing the low-cost experimental platforms. Moreover, the Digital lock-in amplifiers can achieve sub-micron beam position detection accuracy (better than 1 μm) using frequency-shifting techniques, which can improve the stability of free-space laser communication [17-21].

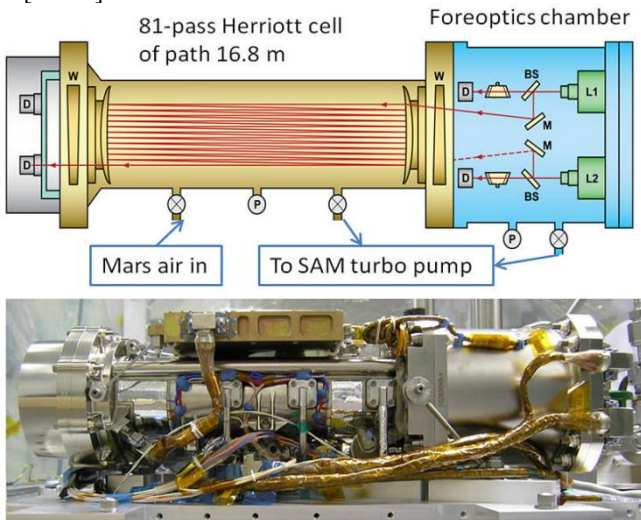


Fig. 1. TDLAS with lock-in amplifier [16]

## 5 Conclusion

Digital lock-in amplifiers can leverage adaptive algorithms, such as Hilbert transform, for real-time, multi-channel signal demodulation, ideal for IoT and smart sensing applications. At the aspect of artificial intelligence, the deep learning functions and algorithms optimize reference signal matching, which further improve weak-signal extraction efficiency in complex environments. For the cross-disciplinary expansion, the group member gives two main angles through the brainstorm: firstly, the Wireless-enabled lock-in amplifiers support real-time air pollutant tracking and portable biosensors for rapid disease biomarker screening such as the methane leak detection; secondly, the integration of optical lock-in amplification and Lazer technology enhances SRS microscopy for early cancer diagnosis, reducing imaging time to

millisecond scales. Hence, this tech can be put into practice of medical surgery. The lock-in amplifier market in Asia-Pacific is projected to grow at a CAGR exceeding 5% (2024–2030), driven by cost-effective FPGA solutions from Chinese manufacturers. Generally, the market of the optical lock-in amplification has great room for growth with magnificent potential.

Optical lock-in amplification technology, with its exceptional SNR, phase sensitivity, and weak-signal recovery capabilities, has become indispensable in quantum science, biomedicine, and industrial sensing. Future advancements in digitization and AI integration will expand its applications beyond laboratories, while cost-effective solutions will accelerate global accessibility. However, challenges such as high-integration design, extreme-environment adaptability, and interdisciplinary collaboration remain critical for breakthroughs. Through continuous innovation and cross-domain synergy, lock-in amplifiers are poised to play a transformative role in environmental monitoring, precision medicine, and next-generation communication technologies.

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