

Advanced Demodulation Algorithms in Optical Interferometry: A Technical Analysis of PGC, TPM, and FPGA Implementations

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Introduction to Modern Phase Demodulation

In the realm of precision measurement and optical engineering, the ability to extract phase information from modulated signals with high fidelity is paramount. Phase demodulation serves as the cornerstone for technologies ranging from **laser interferometry** to **optical fiber vibration sensing**. As industries demand higher resolution, lower noise floors, and greater stability, the algorithms governing signal recovery have evolved from simple analog discriminators to complex, multi-stage digital processing frameworks. This article provides an in-depth technical exploration of modern demodulation algorithms, specifically focusing on **Phase Generated Carrier (PGC)**, **Time-Phase Modulation (TPM)**, and **Nonlinear Fitting** techniques that define the current state of the art.

The primary challenge in phase demodulation lies in the non-linear nature of the interference signal. In a typical interferometric system, the detected intensity is a cosine function of the phase difference. This relationship introduces **signal fading** and harmonic distortion, particularly when environmental factors like temperature fluctuations or mechanical vibrations shift the operating point of the system. To overcome these hurdles, researchers have developed algorithms that not only extract the phase but also compensate for system non-idealities in real-time.

Theoretical Framework of Phase-Modulated Signals

Before diving into specific algorithms, it is essential to establish the mathematical foundation of a phase-modulated optical signal. A standard interference signal in a system utilizing a carrier frequency can be expressed as:

$$I(t) = A + B \cos[\phi + C \sin(\omega t)]$$

Where: **A**: Represents the DC background intensity or the average power of the signal. **B**: Denotes the interference fringe visibility or the AC amplitude. ϕ : The target phase signal containing the physical information (displacement, vibration, etc.). **C**: Is the phase modulation depth, a critical parameter in PGC systems. ω : The angular frequency of the high-frequency carrier signal.

The objective of any demodulation algorithm is to isolate ϕ while eliminating the influence of **A**, **B**, and **C**. Variations in **A** and **B** occur due to light source power fluctuations or fiber bending losses, while variations in **C** (modulation depth) can lead to significant non-linear errors if not properly managed.

Time-Phase Modulation (TPM) Characteristics

Research by **Z. Mao (2015)** highlights the unique properties of **Time-Phase Modulation (TPM)**. Unlike standard phase modulation where the phase shift is a direct mapping of a physical quantity, TPM signals exhibit specific **time-frequency distribution** properties. Analyzing these signals requires nonstationary signal analysis methods, such as the Wigner-Ville distribution or Short-Time Fourier Transforms (STFT), to identify the instantaneous frequency components. TPM is particularly useful in environments where the signal is subject to high-frequency

transients, requiring the demodulator to adapt to rapidly changing signal statistics.

The Evolution of Phase Generated Carrier (PGC) Algorithms

The Phase Generated Carrier (PGC) technique is one of the most widely adopted methods for passive homodyne demodulation in optical fiber sensors. It effectively eliminates the signal fading problem by shifting the signal spectrum into the frequency domain around the carrier frequency and its harmonics.

1. PGC-Differential-Cross-Multiplying (PGC-DCM)

The **PGC-DCM** algorithm, as discussed in the works of **Y. Tong (2012)**, is a foundational method. The process involves multiplying the interference signal by the fundamental carrier ($\cos(\omega_c t)$) and its second harmonic ($\cos(2\omega_c t)$). After low-pass filtering, two quadrature components are obtained, proportional to the sine and cosine of the target phase. By performing a cross-multiplication and subtraction followed by integration, the phase is recovered.

The advantage of PGC-DCM is its ability to handle large dynamic ranges. However, it is highly sensitive to the **modulation depth (C)**. If C deviates from the ideal value of 2.63 radians, the amplitudes of the quadrature components become unbalanced, leading to harmonic distortion.

2. PGC-Arctan (PGC-Atan)

To improve upon DCM, the **PGC-Arctan** method uses the ratio of the fundamental and second harmonic components. By applying the **atan2** function, the phase is directly computed. This method is more robust against variations in the light intensity (parameter **B**) but still requires C to be precisely maintained, typically at 2.63 rad, to ensure the Bessel functions of the first kind $J_1(C)$ and $J_2(C)$ are equal.

3. Improved PGC with Nonlinear Fitting and ODR

Modern iterations, such as those proposed by **X. Liu (2024)** and **Y. Gong (2022)**, incorporate **nonlinear fitting** and **Orthogonal Distance Regression (ODR)**. These advanced algorithms address the Achilles' heel of PGC: the instability of modulation depth and carrier phase delay. By using a nonlinear fitting approach, the algorithm can dynamically estimate the actual modulation depth C and the carrier phase shift in real-time. This reduces the **Total Harmonic Distortion (THD)** to below 1%, even when the modulation depth fluctuates significantly due to environmental stress on the modulator.

Comparative Analysis of Demodulation Methodologies

To assist engineers in selecting the appropriate algorithm for their specific application, the following table summarizes the performance metrics of the primary demodulation strategies identified in recent technical studies.

Algorithm Type	Complexity	Sensitivity to Modulation Depth (C)	Noise Performance	Best Use Case
PGC-DCM	Moderate	High	High SNR required	General fiber sensing
PGC-Arctan	Low	Moderate	Moderate	High-speed displacement
Nonlinear Fitting	Very High	Negligible	Excellent	Precision metrology (THD < 1%)
ODR-Based PGC	High	Insensitive	Superior	Vibration sensing in unstable environments
FPGA-Based SMI	High	Variable	Low	Compact, self-mixing interferometers
DC Phase Tracking	Moderate	N/A	Stable	Michelson Interferometers

Hardware Implementation: FPGA-Based Signal Processing

As noted by **Q. Liu (2021)**, the transition from software-based post-processing to **Field Programmable Gate Array (FPGA)** implementation is a critical trend for real-time applications. FPGA-based demodulators offer the parallel processing power necessary to handle high-frequency sampling and complex algorithmic steps with minimal latency.

The FPGA Workflow

1. Data Acquisition: High-speed ADCs sample the interference signal, often at rates exceeding 100 MSPS to capture high-frequency carrier components.
2. Digital Down Conversion (DDC): The raw data is mixed with digitally synthesized carrier signals (sin and cos) generated by Direct Digital Synthesis (DDS) cores.
3. Filtering: FIR (Finite Impulse Response) or IIR (Infinite Impulse Response) filters are implemented within the FPGA fabric to isolate the quadrature components.
4. Phase Extraction: Algorithms like CORDIC (Coordinate Rotation Digital Computer) are utilized to perform the arctan calculation efficiently without the need for intensive multiplier resources.
5. Real-time Compensation: Modern FPGA designs include logic to monitor the modulation depth and apply correction factors dynamically, ensuring long-term stability.

Case Study: Michelson Interferometer with DC Phase Tracking

Research by **J. Lin (2021)** demonstrates a specialized application for **Michelson Interferometers (MI)**. In many two-way sensing configurations, the DC component of the signal is not constant, leading to drift. The **DC phase tracking algorithm** serves to stabilize the MI by actively monitoring the drift and adjusting the phase of the reference arm or applying a digital offset correction. This is particularly vital in **optical fiber vibration sensing**, where the baseline phase might shift due to thermal expansion of the fiber, which could otherwise be mistaken for a low-frequency vibration signal.

Mathematical Modeling of Harmonic Distortion

To understand why improved algorithms are necessary, we must analyze the source of error in PGC systems. When the modulation depth C is not equal to the target value (e.g., 2.63 for PGC-Atan), the quadrature signals X and Y can be defined as:

$$X = -B J_1(C) \sin(\omega t) \quad Y = -B J_2(C) \cos(\omega t)$$

If $J_1(C) \neq J_2(C)$, the resulting phase estimate $\hat{\phi} = \arctan(Y/X)$ will contain periodic errors proportional to $2\pi(C - C_{\text{target}})$. This manifests as harmonic distortion. The **Improved Algorithm by Y. Gong (2022)** extracts the modulation depth by analyzing the frequency mixing products, effectively normalizing the Bessel coefficients $J_1(C)$ and $J_2(C)$ before the arctan operation. This normalization is what allows for the reported reduction in THD and improvement in measurement linearity.

Practical Implementation and Field Guide

Implementing these algorithms in a real-world sensing system requires careful attention to signal integrity and calibration. Following these steps ensures optimal demodulator performance:

1. Carrier Selection

Select a carrier frequency (ω_c) at least 5 to 10 times higher than the maximum expected frequency of the target signal (ω_s). This ensures that the sidebands of the carrier harmonics do not overlap, which would cause aliasing and non-recoverable distortion.

2. Anti-Aliasing and Filtering

Before the signal enters the ADC, an analog anti-aliasing filter must be used. Once digitized, the Low-Pass Filters (LPF) used after mixing must have a flat passband and a sharp cutoff. Phase-linear FIR filters are preferred to avoid introducing group delay variations that could distort the recovered phase.

3. Calibration of Modulation Depth

In systems without real-time nonlinear fitting, a manual calibration phase is required. The modulation voltage applied to the PZT or EOM (Electro-Optic Modulator) should be adjusted while monitoring the Lissajous figure of the quadrature components. A perfect circle indicates balanced gains and correct modulation depth.

Troubleshooting Common Operational Challenges

Even with advanced algorithms, technical issues can arise during field deployment. Below are common failure modes and their respective solutions.

- **Low Visibility (Signal Fading):** If the interference fringes (parameter B) become too small, the SNR drops, leading to phase jumps. Solution: Implement an Automatic Gain Control (AGC) loop or use polarization-maintaining (PM) fiber to stabilize visibility.
- **Carrier Phase Delay:** Delay between the digital reference carrier and the physical modulation can lead to incomplete separation of quadrature components. Solution: Use a phase-delay compensation algorithm or a Closed-Loop Delay-Locked Loop (DLL) in the FPGA.
- **Non-Linearity in PZT:** Piezoelectric transducers used for carrier modulation often exhibit hysteresis. Solution: Incorporate the nonlinear fitting algorithm (as per X. Liu, 2024) to adapt to the resulting modulation depth variations.
- **Environmental DC Drift:** Large temperature swings can shift the signal beyond the range of the phase-unwrapping algorithm. Solution: Employ the DC phase tracking method discussed by J. Lin to maintain the

interferometer at its optimal quadrature point.

Summary and Broader Implications

The advancement of demodulation algorithms has transitioned from basic signal recovery to a sophisticated discipline of error compensation and real-time optimization. The integration of **Time-Phase Modulation analysis** and **Phase Generated Carrier** techniques with **nonlinear fitting** has pushed the boundaries of what is possible in optical sensing. By achieving Total Harmonic Distortion levels below 1%, these algorithms enable sub-nanometer displacement sensing and ultra-sensitive vibration detection in environments that were previously too noisy or unstable for interferometric methods.

As we look toward the future, the convergence of **machine learning** with traditional signal processing may further enhance these algorithms, allowing for predictive noise cancellation and even higher levels of sensitivity. The technical foundations laid by Mao, Liu, Tong, and others provide the essential framework for the next generation of high-precision optical instrumentation. Engineers and researchers must continue to refine these mathematical models and hardware implementations to meet the burgeoning demands of the semiconductor, aerospace, and geotechnical monitoring industries.

Ultimately, the choice of algorithm—be it a robust ODR-based PGC for industrial sensing or a high-speed FPGA-based SMI for consumer electronics—depends on the balance between computational resources and the required precision. Understanding the deep mechanics of these demodulation strategies is the key to unlocking the full potential of phase-based optical measurement systems.

Tags: **#Demodulation** **#Phase Generated Carrier** **#Optical Fiber Sensing** **#Interferometry** **#FPGA Signal Processing** **#Time Phase Modulation**

