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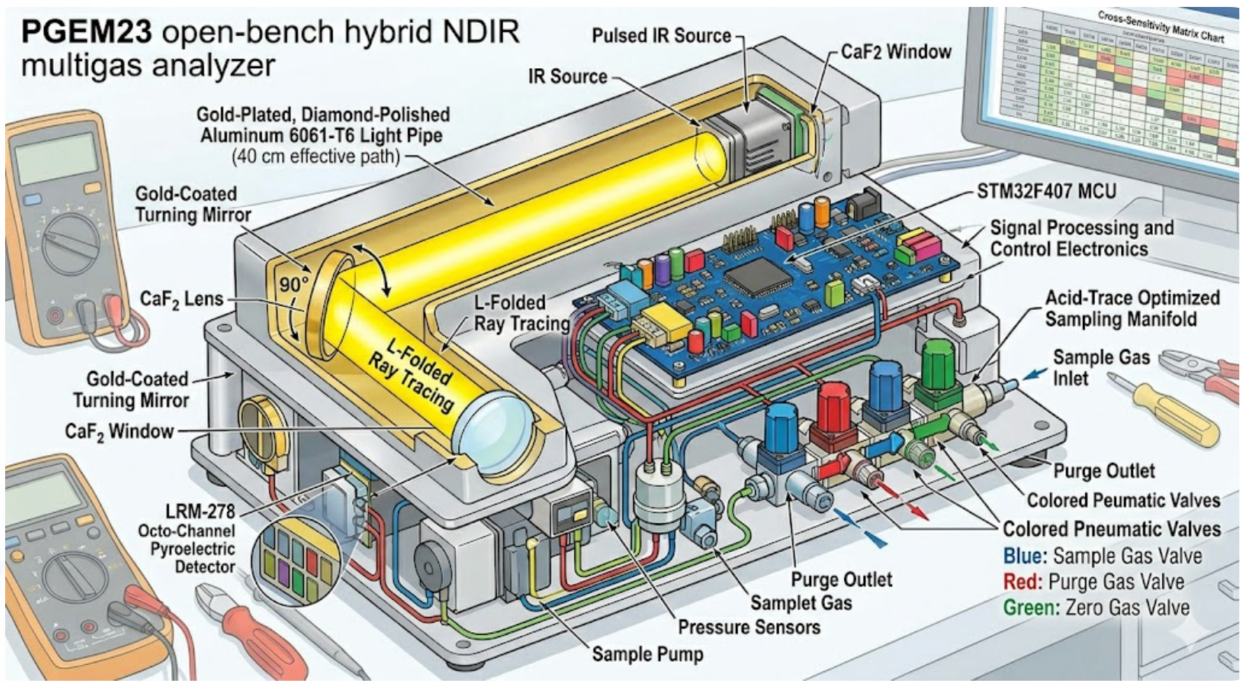
White Paper: Development of A Unified Hybrid NDIR Platform

A technical deep-dive into the engineering of a single-path, high-sensitivity NDIR system. This report details the integration of the **InfraTec LRM-278** octo-channel detector, 40 cm gold-plated folded optics, and advanced cross-sensitivity matrices designed to meet **CPCB (India)**, **ASEAN**, and **GCC** mandates for power, waste, and smelting sectors.



EXECUTIVE SUMMARY AND STRATEGIC REGULATORY ALIGNMENT

1.1 The Single-Bench Paradigm

The PGEM23 represents a paradigm shift in industrial emission monitoring. Traditional multi-gas analyzers often rely on multiple optical benches or disparate sensor technologies to cover the required gas spectrum, which increases mechanical complexity and thermal drift. By contrast, the PGEM23 leverages a unified, single-bench architecture integrated with the InfraTec LRM-278 Octo-Channel Pyroelectric Detector. This consolidation allows for the simultaneous detection of five active gases—Carbon Monoxide (CO), Nitric Oxide (NO), Sulfur Dioxide (SO2), Hydrogen Chloride (HCl), and Hydrogen Fluoride (HF)—within a single optical path.

1.2 Regulatory Compliance Architecture

Designed to address the intricate challenges of global regulatory landscapes, the PGEM23 aligns with strict environmental mandates including India's CPCB, ASEAN frameworks, and GCC regulations.

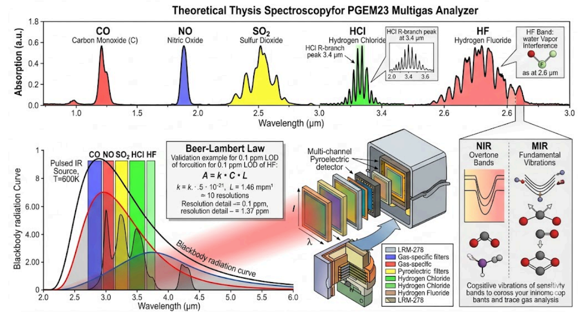
- **CPCB Mandate:** The system is engineered to meet 17 categories of highly polluting industries, specifically targeting acid gas monitoring in hazardous and biomedical waste incinerators.
- **Technical Performance:** The analyzer achieves a response time (T90) of less than 60 seconds and maintains accuracy within +/- 2% of Full Scale (FS) via 4th-order polynomial linearization.
- **Data Reliability:** Redundant SD card storage and a robust firmware architecture target a data capture rate exceeding 99%, far surpassing the minimum 85% requirement.

1.3 Strategic Indigenous Manufacturing

The PGEM23 transitions from a distributor of third-party systems to an Original Equipment Manufacturer (OEM). Furthermore, manufacturing in India aligns with the 'Make in India' initiative, providing procurement advantages in government tenders and proximity to high-growth export markets in the Middle East and Southeast Asia.

THEORETICAL PHYSICS AND SPECTROSCOPY

The fundamental principle behind the PGEM23 is the quantum mechanical interaction between infrared photons and the dipole moments of heteronuclear molecules. When the frequency of infrared radiation matches the natural vibrational frequency of a molecular bond, resonance occurs and the photon is absorbed. While many analyzers utilize Near-Infrared (NIR) overtone bands (1–2.5 µm), these transition probabilities are orders of magnitude lower than fundamental vibrations. Consequently, the PGEM23 operates in the Mid-Infrared (MIR) "Fingerprint Region" (2.5–10 µm) to achieve the sensitivity required for trace gas analysis.



2.1 Precision Spectroscopy for Acid Gases

Hydrogen Chloride (HCl) Spectroscopy

Hydrogen Chloride possesses a strong fundamental absorption band centered at 3.4 µm (2940 cm-1). This specific band features distinct P-branch and R-branch lines resulting from rotational energy level splitting.

- **The Challenge:** Hydrocarbons and Methane (CH4) exhibit significant absorption between 3.3 and 3.5 µm, while water vapor (H2O) further overlaps this region.
- **The PGEM23 Solution:** The design employs a high-precision narrowband filter focused on the R-branch of HCl, which successfully avoids peak methane absorption and ensures high selectivity in complex gas matrices.

Hydrogen Fluoride (HF) Spectroscopy

The measurement of Hydrogen Fluoride represents the most rigorous spectroscopic challenge in the system design.

- **Spectral Dynamics:** The fundamental HF band is located at 2.60 µm (3840 cm-1). Although it has a high absorption coefficient, the regulatory target concentration of 0–10 ppm is exceptionally low.
- **Interference Management:** This wavelength sits on the shoulder of a

massive water vapor band at 2.7 µm. To overcome this, the PGEM23 utilizes an ultra-narrow bandwidth filter (1% FWHM) combined with aggressive H_2O compensation data provided by a dedicated water channel.

2.2 Beer-Lambert Law Optimization & Validation

The relationship between gas concentration (C) and transmitted light intensity (I) is defined by the Beer-Lambert Law: **$I = I_0 \times e^{(-\alpha \cdot C \cdot L)}$**. In terms of Absorbance (A), the formula is expressed as **$A = \alpha \cdot C \cdot L$**.

HF Sensitivity Validation (Trace Gas Baseline)

To ensure compliance with the CPCB Limit of Detection (LOD) of 0.1 ppm, the following spectroscopic sequence is applied to the HF measurement:

- **Molar Absorptivity (k):** 4.2×10^{-4} $ppm^{-1} \cdot cm^{-1}$.
- **Optical Path (L):** 40 cm.
- **Full-Scale Absorbance:** $A = (4.2 \times 10^{-4}) \times (10\ ppm) \times (40\ cm) = 0.168$.
- **Signal Response:** This absorbance level generates a signal drop of approximately 15.5% at the 10 ppm full-scale limit.
- **Resolution:** This translates to a 1.67% signal drop per 1 ppm. At the required 0.1 ppm LOD, the system accurately detects a 0.167% change in signal intensity, which remains well above the detector's noise floor.

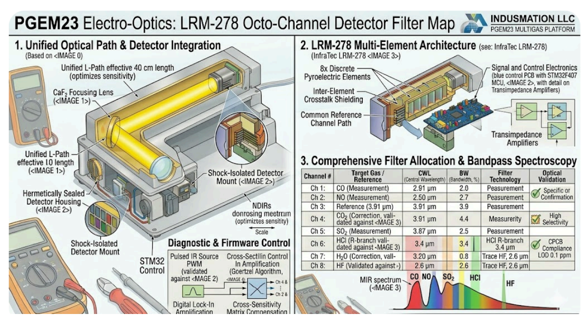
SO2 Measurement Validation (Strong Absorber)

By comparison, Sulfur Dioxide acts as a much stronger absorber at 7.30 µm.

- **Molar Absorptivity (k):** 3.5×10^{-4} $ppm^{-1} \cdot cm^{-1}$.
- **Absorbance at 100 ppm:** $A = (3.5 \times 10^{-4}) \times (100\ ppm) \times (40\ cm) = 1.4$.
- **Signal Response:** This produces a robust signal drop of approximately 75.3% at full scale.
- **Accuracy:** A 1 ppm change in SO_2 results in a signal change of approximately 655 µV, which is 14.5 times higher than the raw electronic noise of the LRM-278 detector. This ensures the system comfortably exceeds the CPCB requirement for ±2% full-scale accuracy.

OPTO-MECHANICAL AND THERMAL ENGINEERING

3.1 Folded-Path "L" Geometry



To achieve the required 40 cm path length within a compact chassis, the PGEM23 utilizes a folded "L" geometry consisting of two 200 mm legs.

- **Optical Guidance:** A flat, 45-degree gold-coated turning mirror reflects the collimated beam between segments.
- **Waveguide Principle:** The internal walls of the light pipe are diamond-polished to a mirror finish (Ra < 0.05 µm) and gold-plated to ensure >98.5% reflectivity across the MIR range.

3.2 Material Science and Optics

- **Calcium Fluoride (CaF_2):** Unlike standard sapphire, which blocks radiation beyond 5.5 µm, CaF_2

windows are used to provide >90% transmission for SO_2 at 7.3 µm.
- **Chemical Resistance:** CaF_2 is resistant to HF acid and insoluble in water, ensuring longevity in harsh industrial environments.

3.3 Active Thermal Management

To prevent acid condensation and thermal drift, the aluminum bench is actively heated to a stable 60°C +/- 0.05°C. This is managed via distributed cartridge heaters and a high-density PID control loop on the microcontroller.

3.4 Octo-Channel Filter Assignment

The LRM-278 detector facilitates simultaneous viewing of the gas sample through eight distinct filters.

- **Measurement Channels:** Dedicated channels for HF (2.60 µm), HCl (3.40 µm), CO (4.65 µm), NO (5.30 µm), and SO_2 (7.30 µm).
- **Reference & Correction:** Channel 3 provides a clean reference signal at 3.91 µm, while Channels 4 and 7 provide correction data for CO_2 and H_2O respectively.

SIGNAL PROCESSING AND SAMPLE EXTRACTION

4.1 Digital Signal Processing (DSP) Architecture

The system is powered by the STM32F407 (ARM Cortex-M4F) microcontroller.

- **Digital Lock-In Amplifier:** The MCU pulses the IR source at a precise 4 Hz modulation frequency.
- **Goertzel Algorithm:** This acts as an infinite-Q bandpass filter to isolate signal amplitude while rejecting DC drift and 50 Hz mains interference.
- **Ratio-metric Normalization:** Every gas signal is normalized against the reference channel (Ratio = V_{gas} / V_{ref}), ensuring readings remain stable even if light intensity drops by 50% due to window fouling.
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4.2 Cross-Sensitivity Compensation Matrix

Because IR absorption bands overlap, the firmware solves a multi-variable matrix equation to decouple gas signals. This logic subtracts interference—such as water

- **Rapid Chilling:** A Peltier chiller utilizing PVDF or glass heat exchangers flash-cools the gas, minimizing residence time to prevent acid loss.
- **Corrosion Resistance:** All sample lines utilize heated Teflon (PTFE) at >120°C, and internal pumps are Teflon-coated to prevent chemical degradation vapor’s effect on NO and HF—ensuring the purity of the reported ppm value

4.3 "Cool and Dry" Extraction Solution

A critical challenge for HCl and HF is their high solubility; if water condenses in the cooling stage, it "scrubs" the target gases.

- **Mist Vaporization:** A heated coalescing probe filter at 180°C vaporizes acid mists before they enter the cooling stage.