

Sulfur Species Detection Using Three-Channel QCL Sensor

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Page 1



ABSTRACT

Researchers at the Institute of Chemical Technologies and Analytics in Vienna, Austria, developed an ATEX-certified sensor to detect hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH), and carbonyl sulfide (COS) in petrochemical process streams. The system integrates three distributed-feedback quantum cascade lasers (QCLs) with wavelength modulation spectroscopy (WMS) and second-harmonic detection for high sensitivity. Laboratory testing with a multipass Herriott cell showed detection limits of 0.3 ppmv for H_2S , 60 ppbv for CH_3SH , and 5 ppbv for COS, with noise-equivalent absorption sensitivities in the 10^{-9} to $10^{-10} \text{ cm}^{-1} \cdot \text{Hz}^{-1/2}$ range. Field trials with an industrial hydrodesulfurization (HDS) unit confirmed reliable performance in fluctuating conditions. This compact sensor enables accurate monitoring of trace sulfur species, supporting safer, more efficient petrochemical operations.

SULFUR EMISSIONS

While the global shift is moving towards renewable energy and cleaner technologies, petrochemical processes remain a cornerstone of the modern economy, supplying fuels, plastics, and countless chemical products that society continues to depend on. These processes are critical for energy and manufacturing, but they also produce byproducts that present significant safety and environmental challenges. Sulfur-containing compounds, in particular, can interfere with refining efficiency, degrade equipment, and pose risks to both workers and surrounding communities.¹ Monitoring these compounds is complicated because of the variety of gas mixtures and extremely low concentrations at which they can still cause damage, making accurate measurements both technically challenging and operationally important. Key refining steps, such as hydrodesulfurization (HDS) and fluid catalytic cracking (FCC) are especially sensitive, as sulfur species can poison catalysts, slow reaction efficiency, and reduce product yield.

Hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH), and carbonyl sulfide (COS) are especially problematic due to their toxicity, corrosive nature, and environmental impact. Even at trace levels, they damage catalysts, while uncontrolled emissions contribute to acid rain and air pollution. Precise detection and monitoring of these gases is essential to maintain safe operations, ensure compliance with environmental regulations, and minimize ecological harm. Accurate sulfur measurements also allow operators to optimize process efficiency, reduce unplanned downtime, and support long-term sustainability initiatives. By addressing these challenges, the petrochemical industry can balance operational performance with environmental stewardship, helping to bridge current energy needs with the global shift toward cleaner technologies.

PROBLEMS AND GOALS

Previous approaches to monitoring sulfur-containing gases in petrochemical processes have faced significant limitations. Traditional methods, including electrochemical sensors, gas chromatography, and fluorescence-based techniques, often lack the sensitivity or selectivity required to detect trace concentrations of H_2S , CH_3SH , and COS in complex gas mixtures.¹ Slow response times and interference from other hydrocarbons further limit their usefulness for real-time process control. Many conventional sensors are also unsuitable for hazardous or explosive environments, restricting their practical deployment in active petrochemical operations. These limitations have made it difficult for operators to maintain both optimal efficiency and strict environmental compliance simultaneously.

Quantum cascade lasers (QCLs) can help solve these challenges for real-time, highly selective, and ultra-sensitive detection of multiple sulfur species simultaneously. QCLs operate in the mid-infrared range, targeting the fundamental molecular vibrations of H_2S , CH_3SH , and COS, which provides significantly greater sensitivity and specificity than traditional sensors. An additional concern that can be avoided is designing a system capable of functioning safely and reliably in industrial and potentially explosive environments by utilizing distributed-feedback (DFB) QCLs for compact and deployable trace gas sensing. By integrating advanced spectroscopic techniques with robust industrial design, researchers can provide petrochemical operators with the ability to accurately monitor sulfur emissions, reduce operational risks, and improve environmental compliance, supporting safer and more sustainable energy production.

METHOD

Researchers from the Institute of Chemical Technologies and Analytics in Vienna, Austria, developed an ATEX-certified sensor to simultaneously detect three sulfur-containing compounds, hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH), and carbonyl sulfide (COS), in petrochemical process streams.¹ The system integrates three distributed-feedback (DFB) quantum cascade lasers (QCLs), with each laser specifically tuned to the mid-infrared absorption band of a single sulfur species. As illustrated in **Figure 1**, using one QCL per target compound ensures full spectral coverage and high selectivity for simultaneous detection, allowing the sensor to distinguish each species even in complex gas mixtures. This approach improves measurement reliability and reduces the potential for cross-interference between gases.

Each QCL was further characterized for operational current, emitted wavenumber, and optical power, as shown in **Figure 2**, to confirm precise alignment with the absorption features of its target species. With the shaded regions of each laser characterization, optimal thermoelectric cooling settings and input currents are realized. Operational points are within 20-30°C,¹ reducing any complex cooling system requirements.

The overall sensor system layout is presented in **Figure 3**, highlighting the three QCLs, optical paths, and the field-programmable gate array (FPGA) that enables wavelength modulation spectroscopy (WMS) with precise system timing and synchronization. The QCLs were driven by Wavelength Electronics' QCL OEM drivers, which provided ultra-stable, low-noise current, which is essential for maintaining precise wavelength and power output. This power

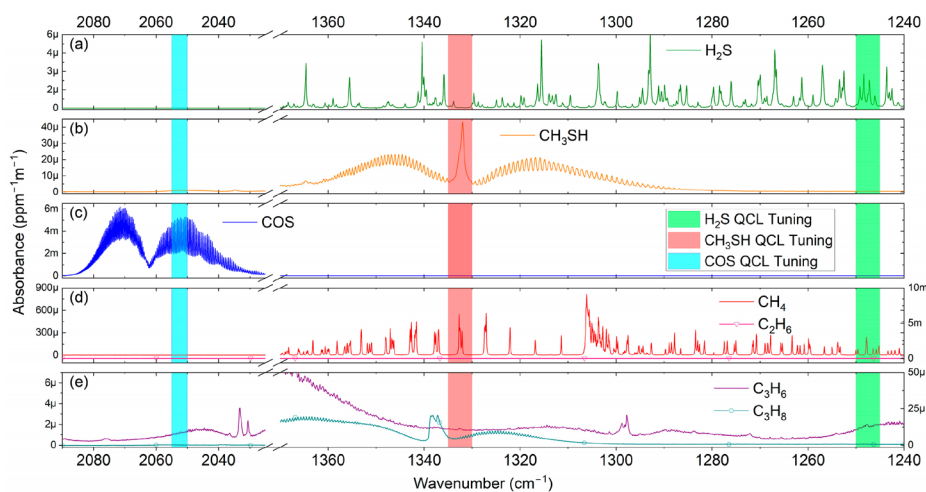


Figure 1. Absorption spectra of the target analytes (1 ppm-m, 25 °C, 1 bar) along with the tuning range of the employed QCLs. (a) H_2S , (b) CH_3SH , and (c) COS . Absorption spectra of the most important hydrocarbon matrices are plotted for CH_4 and C_2H_6 in (d) and for C_3H_6 and C_3H_8 in (e). All spectra are taken from the PNNL database.¹

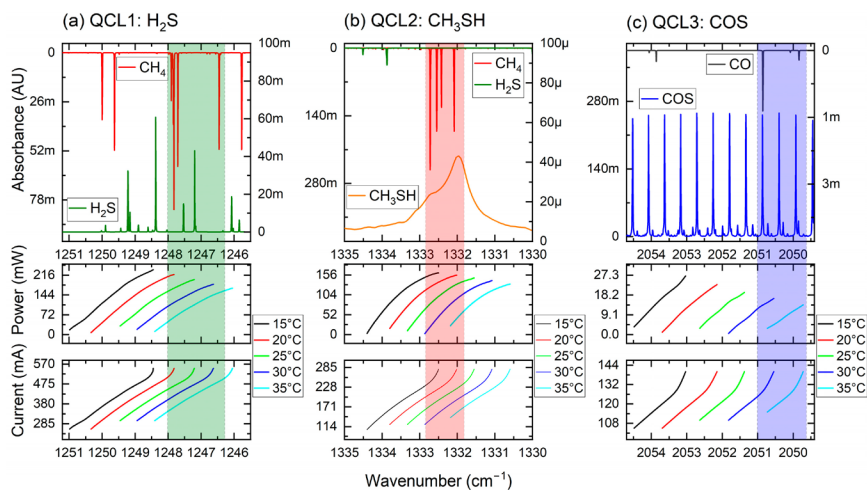


Figure 2. Characterization of the cw-QCLs. Operational current, emitted wavenumber, and attributed optical power are plotted in the lower parts of the figure. In addition, absorption spectra of the target and reference cell analytes, along with the designated operational area (shaded), are plotted in the top parts.¹

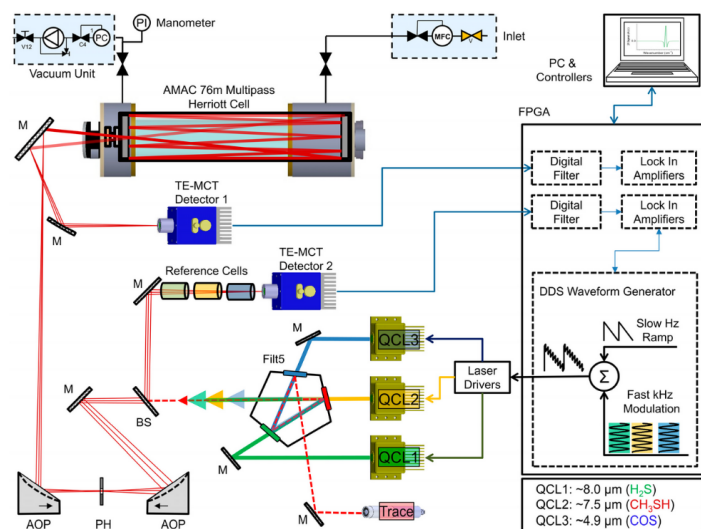


Figure 3. Optical and peripheral layout of the triple-QCL sensor. BS: beamsplitter; M: mirror; AOP: off-axis parabolic mirror; PH: pinhole.¹

electronics were integrated to isolate the laser and system components in the event of a hazardous condition, ensuring safe operation in explosive petrochemical environments. The fully assembled sensor, including the QCLs, optics, electronics, and safety systems, is shown in **Figure 4**, illustrating how all components are compactly integrated for industrial application while maintaining compliance with industrial safety requirements.

To verify performance, researchers applied wavelength modulation spectroscopy (WMS) with second-harmonic detection ($2f$), a common technique for enhancing sensitivity and reducing background noise. Each of the three QCLs was modulated and operated in a time-division multiplexing scheme, enabling the sensor to track hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH), and carbonyl sulfide (COS) simultaneously without cross-interference. A combined signal was applied to each laser injection current, consisting of a fast sinusoidal modulation in the kHz range overlaid on a slow ramp function in the Hz range, which allowed both fine-scale wavelength modulation and broader spectral scanning. For laboratory evaluation, test gases were introduced into a multipass Herriott cell that extended the optical path to 76 meters, ensuring sufficient interaction between the mid-infrared laser light and the trace sulfur species. By flowing known concentrations of each compound through the cell, the team established calibration curves and confirmed a consistent linear response.¹ This approach demonstrated that the sensor design could reliably translate modulation signals into accurate concentration measurements, laying the groundwork for its successful field deployment.

delivery system ensured the lasers operated reliably over long durations, which is critical for sensitive, real-time measurements in industrial environments. The design process also focused heavily on safety to meet ATEX certification standards. The enclosure is pressurized and continuously monitored, with intrinsic explosion prevention and malfunction protection. The method of explosion protection involves a sufficient differential pressure of N_2 protective gas to prevent the ingress of flammable gas, vapor, dust, and fiber, and to prevent any possible ignition.¹ Critical safety

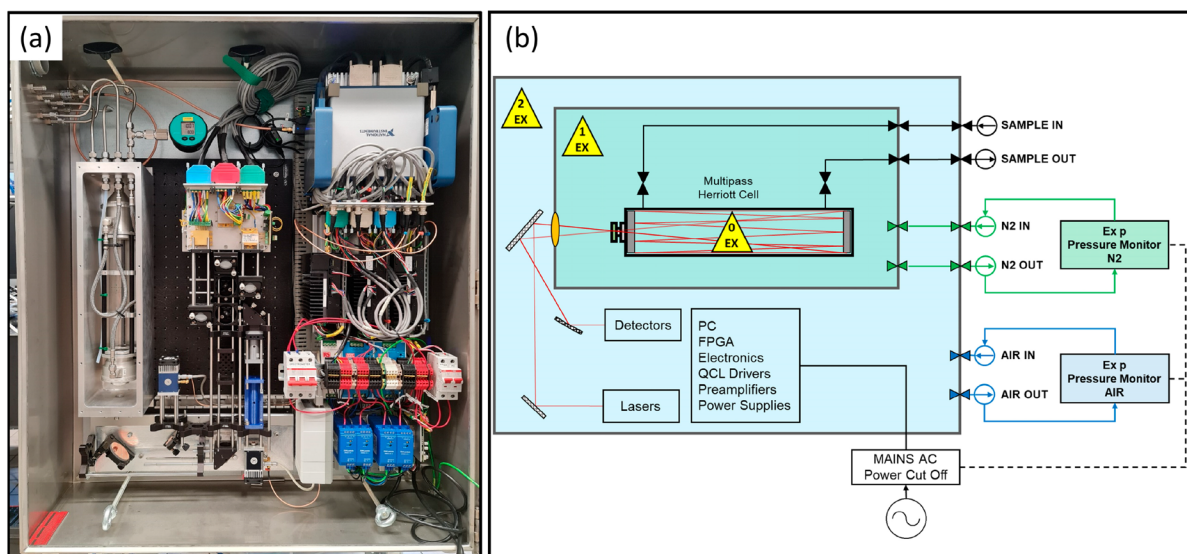


Figure 4. (a) Fully assembled sensor and peripheral components. (b) Piping, instrumentation, and ATEX safety flow diagram.¹

RESULTS

The calibration data used to relate WMS signal to concentration across the tested range is shown in **Figure 5**, demonstrating a consistent response for each target species. These calibration curves support the quantitative conversion of the measured signal to concentration and validate the linear response of the instrument over the calibration interval, supporting the reported limits of detection. Testing in the lab showed that the sensor can achieve sub-part-per-million detection limits for all three sulfur species: 0.3 ppmv for H₂S, 60 ppbv for CH₃SH, and 5 ppbv for COS.

In addition to detection limits, noise-equivalent absorption sensitivities (NEAS) provide more detailed parameters and are defined as the minimum detectable absorption, scaled by both the path length and the noise equivalent detection bandwidth.¹ NEAS for each sulfur species was measured at 5.93×10^{-9} (H₂S), 4.65×10^{-9} (CH₃SH), and 5.24×10^{-10} cm⁻¹·Hz^{-1/2} (COS). **Figure 6** presents the NEAS determination used to derive these sensitivities.

Field deployment with a sampled industrial hydrodesulfurization (HDS) unit confirmed that the ATEX-certified sensor operates reliably under process conditions. Unstable operational conditions provided dynamic concentration fluctuations, fully testing the sensor design. The combined laboratory calibration (**Fig. 5**), NEA analysis (**Fig. 6**), and field validation demonstrate a compact, field-deployable sensor capable of delivering simultaneous, real-time sulfur-species data for petrochemical operations.

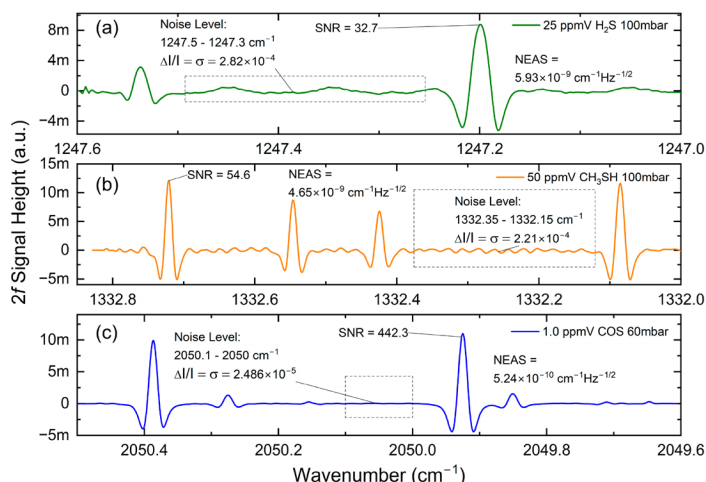


Figure 6. Determination of the noise-equivalent absorption sensitivity (NEAS) of (a) H₂S, (b) CH₃SH, and (c) COS.¹

WAVELENGTH'S ROLE

Researchers utilized three Wavelength Electronics QCL OEM Series drivers to operate the DFB QCLs. These compact, low-noise drivers provided the precise current control required for stable wavelength modulation spectroscopy. Because detection sensitivity depends directly on laser current stability, the low current noise of the OEM drivers was essential to achieving ppbv-level limits of detection. Customizable current ranges from 500 mA to 2 A are available, and RMS noise levels range from 0.4 μ A to 1.3 μ A.

The OEM driver form factor also supported the system's compact, field-deployable design. By supplying each QCL with reliable, stable drive current in a space-saving package, the drivers enabled simultaneous operation of three independent lasers without adding unnecessary bulk or complexity. The QCL OEM driver series also provides maximum safety for the user and the laser with current limits, protection circuitry, over-temperature, and electrical fault protection. This combination of fully featured controllers, engineering support, and responsive technical assistance illustrates how Wavelength Electronics collaborates with high-tech researchers and manufacturers to successfully execute complex, strategic projects while ensuring reliable performance in challenging environments.

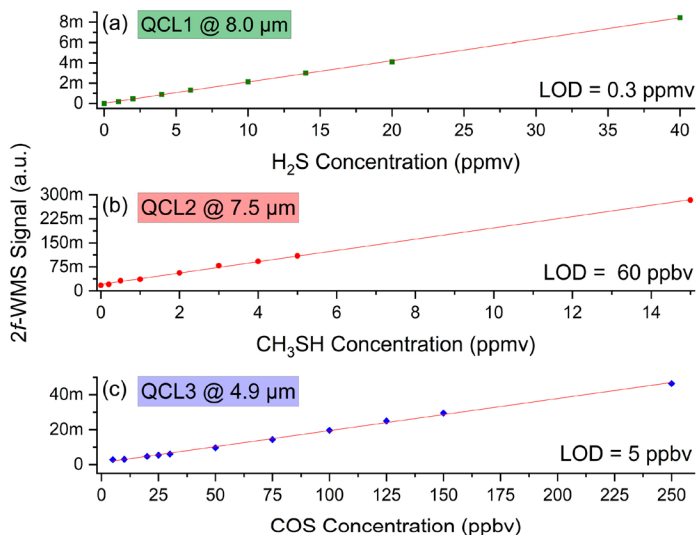


Figure 5. Calibration curves of 0-40 ppmv H₂S, 0-15 ppmv CH₃SH, and 0-250 ppbv COS in N₂. The calculated LOD (3 σ) are 0.3 ppmv for H₂S, 60 ppbv for CH₃SH, and 5 ppbv for COS.¹

REFERENCES

1. Moser, H.; Waclawek, J.P.; Pölz, W.; Lendl, B. ATEX-Certified, FPGA-Based Three-Channel Quantum Cascade Laser Sensor for Sulfur Species Detection in Petrochemical Process Streams. *Sensors* 2025, **25**, 635. <https://doi.org/10.3390/s25030635>

USEFUL LINKS

- QCL OEM [Product Page](#)

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PRODUCTS USED

QCL OEM Series

KEYWORDS

Infrared laser spectroscopy, quantum cascade lasers, QCL, laser sensor, hydrogen sulfide, carbonyl sulfide, methyl mercaptan, methane, HDS, FCC, process monitoring, QCL OEM, laser driver, FPGA

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REVISION	DATE	NOTES
A	September 2025	Initial Release