

Multichannel Distributed Gas Sensing in Free Space by Frequency-Modulated Continuous-Wave Interferometry

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Abstract: We presented a free-space and multichannel distributed gas sensing method based on optical frequency-modulated continuous-wave (FMCW) interferometry. This method leveraged the FMCW's capability for the simultaneous acquisition of the absorption path length and gas spectral information, and introduced a differential absorption spectrum scheme. The high ranging resolution of the FMCW guaranteed the measurement accuracy of the absorption path length, and thus ensured the highly precise retrieval of distributed gas concentrations. Furthermore, by exploiting the FMCW's excellent multiplexing capability, multichannel gas sensing was achieved. In the proof-of-concept experimental demonstration, different concentrations of acetylene gas distributed across three channels with a total of nine monitoring regions were successfully measured. The demonstrated system achieved a ranging resolution of 2 mm and the detection sensitivity of 2 ppm·m. With the advantages of high spectral accuracy, high sensitivity, and high ranging resolution, the proposed method offered a novel approach for the development of distributed spectroscopic gas sensors, targeting challenging applications, such as the monitoring of large-scale gas storage facilities and multi-source industrial gas emissions.

Keywords: Frequency-modulated continuous-wave (FMCW) interferometry; open-path gas sensing; distributed sensing; differential transmittance spectrum; multichannel network

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1. Introduction

Open-path gas sensing plays a critical role in various applications, such as environmental monitoring, leak detection in gas storage facilities, and industrial process supervision [1–3]. In these scenarios, especially during accidental gas leaks, the accurate measurement of gas concentration and its

spatial distribution is essential. The accurate determination of the optical path length is crucial for the reliable gas concentration retrieval, as it directly affects both the spatial resolution and the fidelity of the reconstructed gas concentration distribution. Laser absorption spectroscopy has emerged as a key technology for open-path gas detection, due to its rapid response, high selectivity, and suitability for

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large-area monitoring. As a representative technique, the tunable diode laser absorption spectroscopy (TDLAS) exhibits excellent sensitivity for trace gas detection [4, 5], and shows strong potential for gas field reconstruction in applications such as combustion diagnostics [6–8]. However, the TDLAS lacks spatial localization capability and typically requires complex detection architectures and reconstruction algorithms. The Fourier-transform infrared spectroscopy (FTIR) [9, 10] and dual-comb spectroscopy (DCS) [11–18] offer broadband spectral coverage, enabling simultaneous detection of multiple gas species. Notably, the DCS can achieve sensitivity down to the parts-per-billion (ppb) level. However, both techniques inherently lack spatial localization capability and generally require the integration with the range-finding instruments for position estimation. The differential absorption lidar (DIAL) has demonstrated excellent performance in gas remote sensing and is widely utilized for large-scale atmospheric monitoring. By employing pulsed laser operation, the DIAL is particularly effective for long-distance detection, making it well-suited for applications where broad spatial coverage is prioritized over fine spatial resolution [19–21]. Meanwhile, the advances in integrated mid-infrared photonics have also enabled the demonstrations of open-path gas sensing [22]. Chirped laser dispersion spectroscopy (CLaDS) has recently shown significant potential for long-range open-path detection, with the detection distances ranging from several meters to kilometers and the sensitivity reaching from a few ppmv·m down to ppbv·m levels [23–26], where ppmv and ppbv denote parts per million by volume and parts per billion by volume, respectively, and m denotes the optical path length in meters in the path-integrated concentration unit. When integrated with unmanned aerial vehicle (UAV) platforms, the CLaDS enables three-dimensional localization and the quantification of methane plumes. The field experiments have demonstrated the localization errors ranging from

3 m to 12 m within a 120 m×40 m area [27]. However, the CLaDS is incapable of providing the high-resolution spatial information along the optical path and does not support the multichannel parallel measurement. Although the current open-path gas sensing techniques have made substantial progress in the sensitivity and remote sensing capability, significant limitations remain in simultaneously acquiring the spectral and optical path length information. In particular, the lack of precise optical path length measurement introduces considerable uncertainty in the gas concentration retrieval, especially in the applications that demand high spatial resolution or involve distributed sensing over multiple paths. Moreover, most systems still rely on single-path configurations with sequential scanning, which limits their ability to efficiently identify and track multiple leak sources in complex environments.

The frequency-modulated continuous-wave (FMCW) technology offers a promising solution to these challenges, particularly by enabling precise optical path length measurement, which is critical for quantitative gas analysis. Owing to its high spatial resolution, the FMCW has been widely employed in electronic radar systems for over half a century to provide accurate localization information within the sensing range [28]. In recent years, we have developed a novel optical FMCW interferometric technique that enables the simultaneous acquisition of the gas absorption spectra and the corresponding optical path length [29]. Through continuous improvements, the optical FMCW system has achieved notable enhancements in the gas detection sensitivity, spatial resolution, and dynamic range [30–32]. Recently, the FMCW spectrometer has demonstrated strong potential for the gas identification and spatial localization in free space [33], and its performance has been further enhanced by machine learning approaches [34]. Although previous implementations have validated distributed sensing within compact multipass cells

or folded optical paths [31], further exploration is still required for the large-scale open-path and multichannel distributed gas sensing.

In this study, we presented a free-space and multichannel distributed gas sensing scheme based on the FMCW interferometry. This work represented a fundamental paradigm shift from previous single-point or confined-path FMCW gas probes. While building upon the core principle of simultaneous spectral and ranging information acquisition, the current system introduced a novel and scalable multichannel network architecture with cooperative reflective targets. This architecture enables the sequential acquisition of path-integrated gas concentrations along multiple independent lines of sight. By integrating these measurement methods, the system reconstructed a two-dimensional spatial map of gas distribution, moving beyond point detection to achieve true distributed sensing. This capability to correlate gas presence and concentration across space – which is critical for identifying leak sources and tracking plume movement – was previously unattainable with the FMCW-based methods. Leveraging efficient frequency-division multiplexing [32, 33, 35], the system supported parallel and multichannel detection, laying the foundation for a new class of optical gas imaging networks. This approach is particularly well-suited for the applications requiring high detection accuracy and rapid response over large areas, such as safety monitoring in large-scale gas storage facilities and industrial emission control. It offers a promising basis for the future development of intelligent and automated environmental monitoring systems.

2. Principles

The fundamental principle of the proposed multichannel distributed gas sensing scheme is illustrated in Fig. 1. The system is based on an FMCW interferometer [28] equipped with retroreflectors, which serve as collaborative

reflective targets distributed across the respective lines of different channels. These retroreflectors are essential cooperative targets in the present system, because they provide strong and well-defined return signals required for reliable peak separation, accurate path-length determination, and stable spectral retrieval. For the FMCW spectroscopy relying on arbitrary environmental reflections, a laser with much larger power and a narrow linewidth would be required, which is worthy of further investigation. In operation, a linearly frequency-modulated laser beam is split into the reference arm (R) and the probe arm (P) of a Mach-Zehnder interferometer. In the probe arm, the probe beam is divided by an optical coupler and guided by the optical fiber collimators into multiple free-space sensing channels. These channels are equipped with the retroreflectors distributed in different lines. During propagation, the light passes through gas volumes and is reflected back by corresponding retroreflectors. Due to the differences in optical path length, beat signals at different frequencies are generated. By analyzing these beat signals, the system simultaneously localizes the reflection points along the same line in different channels and acquires the corresponding gas absorption characteristics. The system operates in a hybrid mode: for a given reflection line, the retroreflectors across all N channels are measured simultaneously via frequency-division multiplexing, while the data acquisition proceeds sequentially from one reflection line to the next. This process is repeated for all M lines, enabling the reconstruction of a two-dimensional gas distribution map.

The data processing procedure of the sensing system is illustrated in Fig. 1(b). It is assumed that the system is equipped with N collimators, corresponding to N independent detection channels. Within the sensing region, M lines of retroreflectors are deployed. Let $P_{n,m}$ denote the reflected light from the m th reflection line in the n th channel. The gas spectral information corresponding to different

retroreflectors on the same reflection line can be simultaneously acquired and separated by the frequency-division multiplexing scheme. Additionally, Line 0 is introduced to assist in measuring the optical path length, which is essential for accurately retrieving the gas concentration in the region between Line 0 and Line 1. The raw beat

signals are first processed via the Fourier transform (FT) to separate the signals from different retroreflectors. For each reflector, an inverse FT (IFT) is then applied to recover the corresponding transmission spectrum. Through differential absorption analysis, the gas concentration in each sensing region can be quantitatively determined.

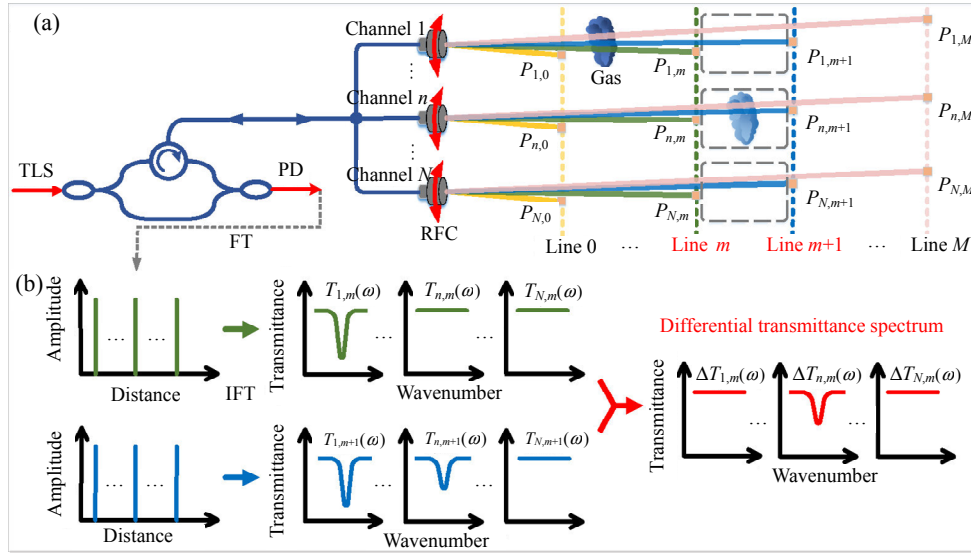


Fig. 1 Fundamental principle of the FMCW-based free-space and multichannel distributed gas sensing: (a) system configuration based on a Mach-Zehnder interferometer (TLS: tunable laser source; RFC: rotatable fiber collimator; PD: photodetector), and (b) data processing procedure for retrieving the transmission spectra and calculating the gas concentration via differential spectral analysis.

The transfer function of the optical field, denoted as $H_{n,m}(\omega)$, is given by [31]

$$H_{n,m}(\omega) = \exp[-j\tilde{k}(\omega)L_{n,m}] = \exp\left[-j\left(\frac{\omega}{c}\eta(\omega) - j\frac{\alpha(\omega)}{2}\right)L_{n,m}\right] \quad (1)$$

where $\tilde{k}(\omega)$ is the complex wavenumber, ω is the angular optical frequency, j denotes the imaginary unit, c is the speed of light in vacuum, and $L_{n,m}$ is the absorption path length of the m th sensing region in the n th channel. Here, $\eta(\omega)$ is the refractive index, and $\alpha(\omega) = \alpha(\omega)\rho_{n,m}$ is the absorption coefficient, where $\alpha(\omega)$ is the gas absorption cross-section and $\rho_{n,m}$ is the gas molecular number density. In the FMCW interferometer, the detected beat signal arises from the interference between the reference light and the probe light returned from the retroreflectors, thereby carrying both the absorption and dispersion

information. The system output voltage, based on the detector response, can be expressed as

$$U(\omega) = \sum_{n,m} 2C_{n,m} \sqrt{I_R I_{P_{n,m}} H_{n,m}(\omega) \cos(\omega\tau_{n,m})} \quad (2)$$

where I_R is the reference light intensity; $I_{P_{n,m}}$ is the probe light intensity from the m th retroreflector in the n th channel; $C_{n,m}$ is a parameter that accounts for the detector responsivity, reflector reflectivity, and optical losses; and $\tau_{n,m}$ is the relative time delay between the reference light and the probe light returned from the m th retroreflector in the n th channel. Due to the different time delays, the beat signals from different retroreflectors exhibit distinct frequencies and can be separated in the time/spatial domain via the FT. Subsequently, applying an IFT to each separated beat component yields:

$$U_{n,m}(\omega) = C_{n,m} \sqrt{I_R I_{P_{n,m}} H_{n,m}(\omega) \exp(j\omega\tau_{n,m})} \quad (3)$$

Focusing on the absorption characteristics, the

spectral transmittance at each retroreflector is defined as

$$T_{n,m}(\omega) = \frac{|U_{n,m}(\omega)|^2}{C_{n,m}^2 I_R I_{P_{n,m}}} = \exp(-\sigma(\omega) \rho_{n,m} L_{n,m}). \quad (4)$$

To analyze the spectral information between adjacent retroreflectors, differential spectral analysis is applied to obtain the path-integrated concentration difference as

$$\begin{aligned} \Delta \rho_{n,m} L_{n,m} &= \rho_{n,m} L_{n,m} - \rho_{n,m-1} L_{n,m-1} \\ &= \frac{\ln(T_{n,m-1}/T_{n,m})}{\sigma(\omega)}. \end{aligned} \quad (5)$$

Consequently, the multichannel distributed gas concentrations are retrieved by using the Beer-Lambert law.

3. Experiment

The experimental setup of the proposed FMCW-based free-space and multichannel distributed gas sensing system is shown in Fig. 2. It primarily consisted of a Mach-Zehnder

measurement interferometer and a Michelson auxiliary interferometer. A tunable laser source (TSL-770, Santec, Japan) emitted a frequency-modulated laser with a wavelength scanning range of 0.6 nm (1 519.8 nm–1 520.4 nm), corresponding to a wavenumber range of 6 577.22 cm⁻¹–6 579.81 cm⁻¹, a tuning rate of 10 nm·s⁻¹, a linewidth of 60 kHz, and the average output power of 10 mW. After being split by an optical coupler, a small portion of the laser was directed into the auxiliary interferometer to generate a stable sinusoidal beat signal for correcting the nonlinear distortion during frequency tuning. The remaining main optical power was injected into the Mach-Zehnder interferometer to perform gas detection. To compensate for the phase noise caused by laser tuning nonlinearity, the system employed a Hilbert resampling method to reconstruct the original signal acquired from the main interferometer at equal frequency intervals.

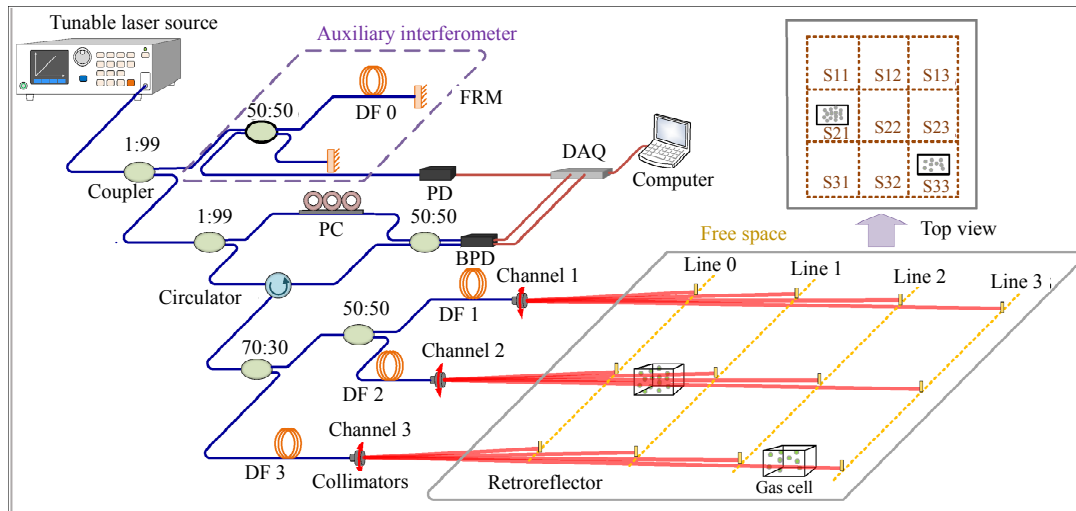


Fig. 2 Experimental setup of the FMCW-based free-space and multichannel distributed gas sensing scheme. (DF: delay fiber; FRM: Faraday rotation mirror; PC: polarization controller; PD: photodetector; BPD: balanced photodetector; DAQ: data acquisition card). In the present experiment, line-to-line switching was achieved by manual rotation of the collimators. Data acquisition was performed sequentially, with signals in the same line being processed simultaneously.

In the main interferometer, approximately 1% of the light used as the reference beam was adjusted by a polarization controller to match the polarization state of the probe path. The remaining 99% of the light serving as the probe beam was routed through a

fiber circulator, and then split into three beams of nearly equal optical power using optical couplers. After traveling through the delay fibers of lengths 25 m, 28 m, and 32 m, respectively, the laser was collimated into free space by optical collimators

(F810APC-1550, Thorlabs, USA) and then directed into three sensing channels. Each sensing channel contained four sequential lines of retroreflectors (Line 0–Line 3), forming three sensing regions between them. It is important to note that the reflectors within a single channel were not positioned in a straight line. Instead, they were deliberately arranged with the lateral offsets to prevent the front reflectors from occluding the optical path to the rear ones. In our configuration, the blind zone was mainly determined by the beam diameter at the reflector position. Based on the collimator specifications (the waist diameter: 7.0 mm; full-angle divergence: 0.016°), the beam diameter was approximately 16.5 mm at 34 m and 34.9 mm at 100 m. Therefore, the occluded region associated with a single upstream reflector remained on the centimeter scale and was negligible in the present four-line demonstration. Two 20-cm transparent gas cells, filled with 5 900-ppm and 4 485-ppm acetylene gases, respectively, were placed in sensing regions S21 and S33 to simulate the leakage scenario depicted in Fig. 1. These gas

cells were tilted at a slight angle relative to the incident beam to minimize their reflection signals and prevent interference with the measurements from the retroreflectors. The beat signals were detected by an AC-coupled balanced photodetector (PDB1008, inSight, USA) with a detection bandwidth of 80 MHz and recorded using a data acquisition card (PCIe-69834, JYTEK, China) at a sampling rate of 20 MHz. After acquiring the beat signals from one line of retroreflectors, the measurement sequentially switched to the next by manually rotating the optical collimators, and this process was repeated until the signals from all four lines had been collected.

4. Results and analysis

Figure 3(a) shows the beat signals after correction for laser tuning nonlinearity using the Hilbert resampling method. These signals were transformed into the spatial domain via the FT, enabling the separation of the multichannel reflected signals, as depicted in Fig. 3(b).

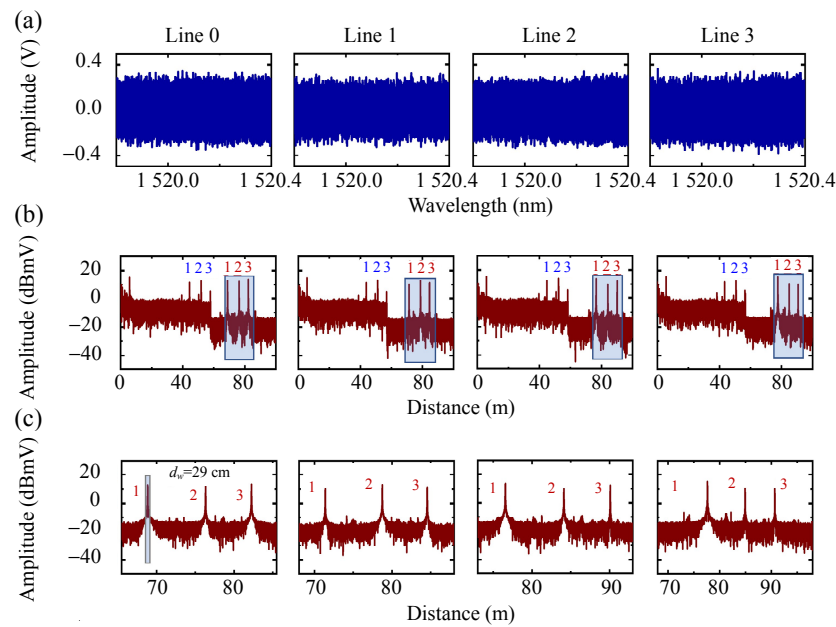


Fig. 3 Experimental results of the FMCW-based free-space and multichannel distributed gas sensing: (a) beat signals acquired from four lines (Line 0–Line 3), each containing three channels, (b) corresponding FT spectra, where the reflection peaks from the fiber collimators (blue labels) and retroreflector targets (red labels) were identified, and (c) enlarged views of the retroreflector peaks highlighted in (b). A 29-cm window centered on each red-labeled peak was selected for the IFT operation to extract the channel-resolved transmission spectra.

The system's ranging resolution Δl was estimated to be approximately 2 mm, determined by $\Delta l = c/2\eta\Delta\nu_{\text{tuning}}$, where c is the speed of light in vacuum, η is the refractive index of the propagation medium, and $\Delta\nu_{\text{tuning}}$ is the laser frequency tuning range. This high ranging resolution ensured highly accurate localization of each retroreflector and, consequently, precise determination of the gas absorption path length—a critical parameter for quantitative concentration retrieval. The integration of precise metrology with spectroscopy enables the distributed sensing capability demonstrated here. The high ranging resolution (2 mm) provided practical advantages for accurate leak localization and for resolving the plume-related features before complete mixing. Moreover, this fine resolution was crucial for measurement integrity: it allowed the system to unambiguously distinguish the cooperative retroreflector signals from the stray background reflections, thereby eliminating the potential source of the spectroscopic error and ensuring the accurate determination of the gas absorption path length. It should be emphasized that the reported 2 mm value referred to the intrinsic FMCW ranging resolution for reflector localization and path-length determination, rather than the spatial sampling interval of the reconstructed gas-concentration map.

In contrast to the millimeter-scale ranging resolution, the spatial sampling interval for the gas concentration in the present system was approximately 3 m, as determined by the spacing between the adjacent retroreflectors in the experimental configuration. The reflection peaks corresponding to the collimators and retroreflectors were identified and labeled with the blue and red numbers in Fig. 3(b).

Several other high-intensity reflection peaks were attributed to the strong internal reflection points within the optical path. The distances from the collimators to the four reflection lines were measured for each channel as follows: Channel 1 – 24.430 m, 27.665 m, 31.795 m, and

34.289 m; Channel 2 – 24.416 m, 27.667 m, 31.812 m, and 34.267 m; Channel 3 – 24.410 m, 27.622 m, 31.827 m, and 34.238 m.

A rectangular window with the width of $d_w = 29$ cm was applied in the distance domain to isolate the reflection peaks of the three channels. After the FT, each retroreflector appeared as a localized peak in the distance domain. The signal amplitude decreased rapidly with distance: at approximately 20 cm from the peak center, the amplitude had already dropped by about 20 dB, and at around 2 m, it approached the noise floor of the system. In our setup, the optical-path differences introduced by the delay fibers were greater than 6 m; consequently, the inter-node crosstalk was negligible for the present channel configuration. Although the long delay fibers improved the channel separation, they also occupied a larger portion of the available distance-domain window, thereby increasing the demands on the acquisition hardware for future scaling, including the available sampling span, data window length, and processing load. Future scalability will therefore require a better balance between robust channel separation and efficient distance-budget utilization. Applying the IFT to the selected peaks (red indices in Fig. 3(b)) yielded their individual transmission signals according to (3), and the corresponding transmission spectra were then obtained using (4). The periodic oscillation noise, originating from the spectral leakage during the FT process, was mitigated using a Savitzky-Golay filter, and its impact on the retrieved path-integrated concentration was verified to be less than 1%. The twelve transmission spectra, corresponding to the three channels and four reflection lines, are shown in Fig. 4. The baseline transmittance values slightly above 1 were caused by the residual fluctuation noise after normalization. The spectral resolution, given by the formula $\Delta\nu_{\text{res}} = c/2\eta d_w$, was estimated to be approximately 0.017 cm^{-1} (or 0.52 GHz), which was about 10% of the acetylene absorption linewidth and thus sufficient to meet the requirements for highly selective gas detection.

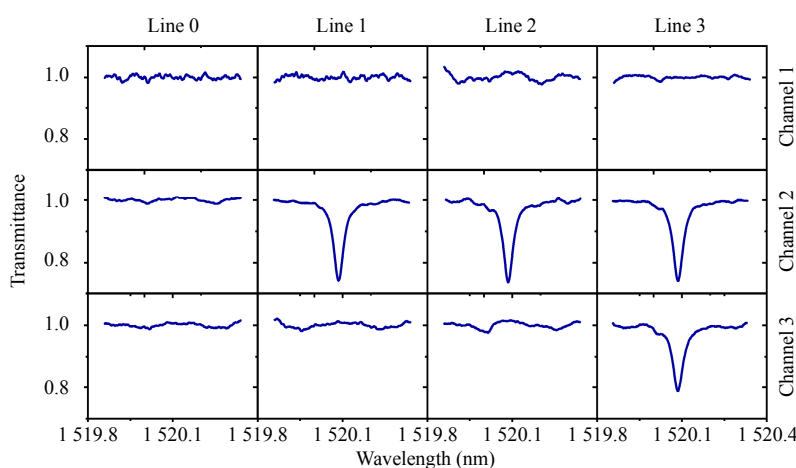


Fig. 4 Retrieved transmission spectra for the three sensing channels, each with four reflection lines, obtained by averaging 20 consecutive sweeps.

For each reflection line, the signals from all sensing channels were acquired simultaneously during a single FMCW wavelength sweep via frequency-division multiplexing. The acquisition of different reflection lines was performed sequentially by rotating the collimator. In the present setup, each spectral acquisition consisted of the laser sweep time of approximately 0.06 s, followed by a settling interval of 0.25 s. To improve the signal-to-noise ratio (SNR), each spectrum shown in Fig. 4 was obtained by averaging 20 consecutive sweeps, resulting in the effective acquisition time of 6.2 s per line. Consequently, the total time required to acquire a complete four-line dataset was approximately 50 s. Of this, the effective acquisition time for the four lines was 24.8 s in total; approximately 10 s was required for the data transfer; the remaining time was mainly consumed by offline data processing. This frame time just reflected the current proof-of-concept configuration and could be substantially reduced in future implementations through faster wavelength sweeping, reduced averaging when the signal conditions permit, automated line switching, and parallelized optical hardware. In addition, the optimization of data transfer and real-time processing would further improve the practical mapping frame rate. The current approximately 50 s frame time limits the

measurement of rapidly evolving gas plumes and mainly arises from the proof-of-concept implementation, including sequential line acquisition, signal averaging, data transfer, and offline processing. Faster swept sources, such as the silicon-photonics integrated lasers [36], reduced averaging, automated/parallel optical switching, and real-time processing could reduce the frame time to the second level in future systems, improving applicability to the dynamic gas-field measurement.

The path-integrated concentration was retrieved by fitting the reconstructed transmission spectra using the line-by-line simulations from the HITRAN2020 database. A Voigt line-shape model was adopted, with the broadening parameters taken from the high-resolution transmission molecular absorption database (HITRAN), assuming the pressure of 1 standard atmospheric pressure (atm) and the temperature of 296 K. The fitting window was restricted to 6577.48 cm^{-1} – 6579.55 cm^{-1} , covering the isolated C_2H_2 absorption line used in this work. Since a rectangular IFT window was used, the reconstructed spectra exhibited a sinc-shaped instrument line shape (ILS) with a spectral resolution of 0.52 GHz. No apodization was applied. To quantify the resulting impact on the concentration retrieval, we varied the window length by $\pm 20\%$ and also performed the HITRAN-based

fitting after convolving the Voigt profiles with a sinc kernel. In both cases, the retrieved path-integrated concentration changed by less than 2% for the present configuration.

As described by (5), the transmission spectra corresponding to different retroreflector lines within each channel were sequentially divided to perform the differential spectral analysis. Since the FMCW system simultaneously provided the distance to each retroreflector, the absorption path length could be precisely determined. Through spectral fitting, the path-integrated gas concentration was calculated from the measured transmittance. Consequently, by combining positional information with the concentration results, the gas concentration distribution across multiple sensing paths was obtained. The measured gas transmission spectra for all three channels are shown in Fig. 5(a). In Channel 1, as expected, no gas absorption features were observed between the retroreflector lines. In Channel 2, gas absorption occurred between Line 0 and Line 1, while in Channel 3, the absorption was also observed between Line 2 and Line 3. The multichannel gas leakage distribution map, shown in Fig. 5(b), was derived by consolidating data from the three channels. In Fig. 5(b), the vertical axis represents the channel number, while the horizontal axis corresponds to the four retroreflector lines. The color bar indicates the spectral transmittance, which

decreased as the path-integrated concentration increased. The results were in good agreement with the experimental setup shown in Fig. 2. The path-integrated gas concentrations measured experimentally in the two target sensing regions (S21 and S33) were 1 140 ppm·m and 928 ppm·m, respectively, closely corresponding to the assumed concentrations of 1 180 ppm·m and 897 ppm·m. The deviation was only 3%, clearly demonstrating the high accuracy of the proposed system. The error budget analysis indicated that laser frequency tuning nonlinearity was the dominant source of uncertainty. The transmittance measurement uncertainty, which represented the second largest contribution, could be further attributed to the residual etalon fringes (1.14%), the detector noise including the RIN/thermal noise (0.50%), and the data-processing effects (0.85%), yielding a combined contribution of 1.51%. The geometric path-length uncertainty arose from the slight gas-cell tilt introduced to suppress the parasitic reflections; the tilt angle was estimated to be about 5° – 10° , corresponding to the relative standard uncertainty of about 0.57% for the path-length term. The resulting combined relative standard uncertainty was 2.3%, corresponding to the expanded uncertainty of 4.6%, which was consistent with the experimentally observed agreement of approximately 3%.

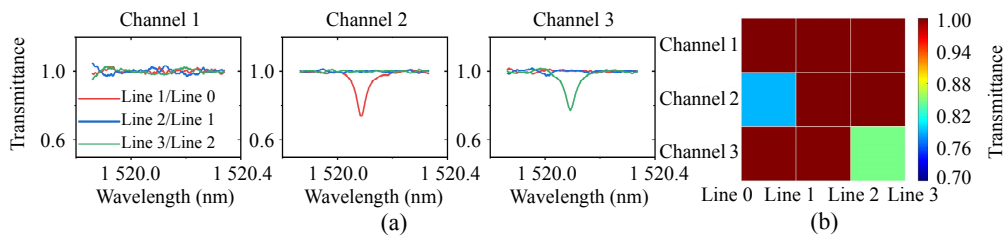


Fig. 5 Leakage distribution across the three detection channels and corresponding gas concentration heatmap: (a) spatial distribution of gas leakage across the three channels, (b) heatmap of the path-integrated gas concentration derived from the multichannel analysis. Line 0–Line 3 denote the four retroreflector lines. The vertical axis represents the channel number (Channel 1–Channel 3), while the horizontal axis (Line 0–Line 3) corresponds to the four retroreflector lines. The color bar indicates the spectral transmittance.

The differential equation (5) assumes that the common background variations exist between the adjacent measurement. Although this assumption

was valid under our stable experimental conditions, it might be challenged in dynamic field environments due to the factors such as atmospheric

turbulence. This consideration primarily concerned the highly dynamic or long-range field deployments, rather than the controlled laboratory-scale configuration demonstrated here. A preliminary first-order estimate indicated that, under representative horizontal-path turbulence conditions, the resulting concentration retrieval error was on the order of 3%–10% at 34 m for a moderate absorption signal, and might become larger for weaker absorption or longer propagation distances. The possible mitigation strategies include the model-based joint fitting of gas concentration and baseline variation, the signal-decomposition methods, such as empirical mode decomposition (EMD) and variational mode decomposition (VMD), as well as the data-driven baseline correction or denoising based on artificial neural networks (ANNs) and convolutional neural networks (CNNs). The practical field applications may also involve multiple gases and particulate matter. Spectral overlap can reduce the concentration retrieval accuracy, while particulates may cause attenuation, baseline distortion, and diffuse backscattering, thereby affecting both detection accuracy and spatial reconstruction. The possible mitigation strategies include spectral-window selection, multi-component fitting, baseline correction, temporal averaging, and FFT-domain spatial filtering. These effects remain to be systematically characterized under the practical field conditions.

To assess the measurement stability and detection limit of the sensing system, an Allan-Werle variance analysis [37] was performed over a 1 000-s period using the acetylene gas at a concentration of 4 400 ppm. The resulting Allan-Werle deviation curve over the 1 000-s measurement period is shown in Fig. 6. Under these stable laboratory conditions, the corresponding detection sensitivity was 15 ppm·m at 1 s, 6 ppm·m at 10 s, and improved to 2 ppm·m at the averaging time of 147 s. Here, the averaging time denotes the integration time applied to the same 1 000-s dataset in the Allan-Werle analysis. Beyond this point, the Allan deviation exhibited a

slight increase followed by weak oscillations. The post-minimum uplift was attributed to the onset of the flicker-type noise processes, while the oscillatory behavior at long averaging times originated from the slow drifts of the interference fringes in the optical path. This behavior reflected the transition from the white-noise dominance at short averaging time to the long-term stability limitations governed by the low-frequency noise and the fringe drift. The values obtained at the short averaging time benchmark the system's transient detection capability against other open-path techniques. The corresponding noise equivalent absorption coefficient (NEA) was evaluated to be $1.5 \times 10^{-4} \text{ cm}^{-1}$, demonstrating the excellent detection sensitivity of the system. The upper end of the usable concentration range was further estimated from the absorption saturation behavior. We used the absorbance $A = -\ln(T)$ and defined a practical near-saturation boundary at $T = 0.01$ ($A = 4.605$). This gave an upper limit of $1.73 \times 10^4 \text{ ppm} \cdot \text{m}$, equivalent to about 500 ppm C_2H_2 over a 35 m effective path. Above this level, the line-center transmission became very weak, so the retrieval increasingly relied on the absorption wings, and the uncertainty caused by insufficient optical power and reduced SNR became more significant. The usable dynamic range was about 4 orders of the magnitude.

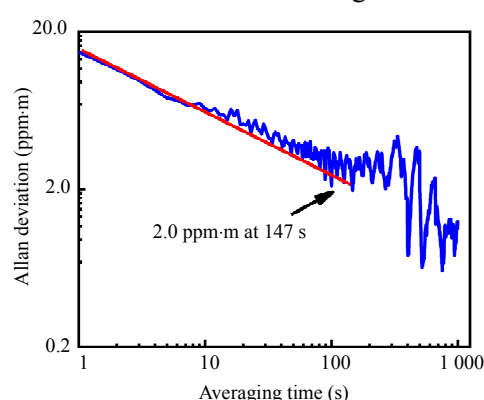


Fig. 6 Allan-Werle deviation obtained from continuous measurement of 4 400-ppm acetylene over a 1 000-s period.

From a practical deployment perspective, we further examined the optical power budget, the reflector requirements, and the effects of turbulence

and platform motion. The F810APC-1550 collimator had a full-angle divergence of 0.016° , giving a beam expansion of 14 mm per 100 m. At the maximum tested distance of 34 m, the returned beat-note peaks showed the FFT-domain SNRs of 31 dB–40 dB, which were sufficient for the stable recovery of the normalized transmission spectra. For a monostatic retroreflector link, the received power scaled as $1/R^4$; extrapolating from 34 m to a 100-m scale implied an approximately 18 dB reduction and an estimated SNR of 13 dB–22 dB, still adequate for the spectral retrieval. This scaling illustrated the power-range trade-off without implying a specific operating limit. At a 100-m scale, the beam diameter was 30 mm–35 mm, which was well matched to the 25 mm–50 mm corner-cube retroreflectors. Their angular deviation (< 3 arcsec, or < 2 mm at 100 m) was far smaller than both the beam footprint and the receiver aperture, ensuring the high collection efficiency and good alignment tolerance. The atmospheric turbulence over tens of meters introduced scintillation and beam wander, but these effects were modest and effectively averaged out by the relatively large apertures.

In future field deployments, a nearly linear and collinear retroreflector arrangement – such as along a pipeline – could cause the upstream reflector to create a substantial occlusion blind zone. The length of this blind zone is approximately given by the reflector size divided by the beam-divergence half-angle, thereby hindering the access to the downstream reflectors. A possible solution is to use the UAV-mounted or other mobile reflective targets. However, this would fundamentally transform the system from a static cooperative-target network into a dynamic scanning architecture, introducing new requirements for precise time synchronization, compensation of the motion-induced Doppler/frequency perturbations, and dynamic target localization. The reliable georeferenced concentration mapping would further require the fusion of the FMCW ranging with the platform pose information.

These aspects will need to be addressed in future implementations.

The demonstrated performance provided a foundation for assessing the system's scalability. In the current configuration, the power budget analysis indicated an operational range exceeding 100 m, which was primarily governed by the available optical power and the associated SNR. This range can be extended to several hundred meters through component upgrades, such as higher-power lasers and larger-aperture optics. However, to achieve the reliable kilometer-scale operation, the dominant challenge shifts to mitigating the impact of the laser phase noise on the interferometric signal. The future system scaling will, therefore, critically depend on the phase noise compensation algorithms to suppress this fundamental limitation. In addition, the hardware-level improvements – such as lasers with the narrower linewidth, improved phase-reference stability, and enhanced thermal/mechanical isolation of the interferometric system – may further improve the phase stability in the future long-range implementations. In practice, the maximum number of channels is limited by the available laser power, since power sharing reduces the per-channel SNR. For the present system, with the maximum laser output power of 30 mW, the minimum acceptable per-channel optical power was estimated to be 1 mW, corresponding to about 21 channels when accounting for an additional transmission factor of 0.7 after the circulator. More channels could in principle be supported with higher launched power, for example, by using an erbium-doped fiber amplifier (EDFA).

For comparison with prior work, Table 1 summarizes the representative prior FMCW implementations and other open-path gas sensing techniques. The comparison emphasizes the sensing modality, resolution metric, minimum detectable concentration (MDC), and multichannel/distributed capability. The resolution values in Table 1 are defined differently across the sensing modalities and

are therefore not directly comparable. In this work, 2 mm referred to the intrinsic FMCW ranging resolution, whereas the spatial sampling interval of the demonstrated gas-concentration map was approximately 3 m. Where applicable, the MDC values were normalized to a 1-Hz bandwidth assuming white-noise scaling, while the techniques reporting different physical metrics or path-averaged concentrations were indicated accordingly. The comparison highlights the inherent trade-offs among the resolution metric, channel architecture, distributed sensing capability, and detection sensitivity across the different approaches. The established path-integrated or range-resolved techniques, such as the DIAL, CLaDS, and DCS

offer high sensitivity for specific applications, but generally do not provide simultaneous multichannel distributed gas mapping. In contrast to the prior FMCW demonstrations, which were primarily restricted to multipass cells or controlled settings, the present work demonstrated a free-space and multichannel distributed architecture. Owing to the fundamental differences in sensing modality, a direct quantitative comparison under identical operating conditions is generally not feasible across these techniques. Accordingly, the superior ranging resolution demonstrated here referred to the intrinsic distributed resolving capability enabled by the FMCW ranging mechanism, rather than to a direct sensitivity advantage under the matched conditions.

Table 1 Comparison of representative open-path gas sensing techniques.

Technique	Sensing mode	Resolution metric	MDC (normalized to 1 Hz bandwidth)	Multichannel/distributed capability
DIAL [20]	Range-resolved	150 m–600 m	$\sim 0.1 \text{ g}\cdot\text{kg}^{-1} (\text{H}_2\text{O}, 25 \text{ min})^*$	No
CLaDS [26]	Path-integrated	N/A	$2.9 \text{ ppm}\cdot\text{m}/\sqrt{\text{Hz}}$	No
DCS [11]	Path-integrated	N/A	$< 2 \text{ ppm}$ (path-averaged, CO_2 , 5 min)**	No
FMCW [30]	Multipoint	1.3 mm	$30 \text{ ppm}\cdot\text{m}/\sqrt{\text{Hz}}$	No
FMCW [38]	Multichannel	20 μm	N/A	Multichannel only
This work	Distributed	2 mm***	$24 \text{ ppm}\cdot\text{m}/\sqrt{\text{Hz}}$	Both

*Reported in the mass mixing ratio; not directly comparable to the absorption-based MDC.

**Reported as the path-averaged concentration over a fixed optical length; not converted due to unspecified path length.

***In this work, the reported 2 mm value denoted the intrinsic FMCW ranging resolution, whereas the spatial sampling interval of the demonstrated gas-concentration map was approximately 3 m, determined by the spacing between adjacent retroreflectors.

At larger spatial scales and under more turbulent atmospheric conditions than those explored in the present laboratory demonstration, the environmental perturbations can affect the accuracy of the concentration retrieval. Although the system measures the path-integrated absorbance, the concentration is obtained through inversion based on the Beer-Lambert law, which requires accurate transmission spectra and reliable estimates of the optical path length. The atmospheric turbulence may introduce intensity scintillation that distorts the baseline of the transmission spectrum and may also broaden or distort the distance-domain reflection peaks, thereby affecting the retrieved optical path length. These effects propagate into the errors in the inferred gas concentration. Addressing such environmental influences motivates the use of

turbulence-aware data selection, averaging strategies, and environmental compensation in the future field deployments. The present laboratory demonstration provides a controlled benchmark for identifying and quantifying these effects.

5. Conclusions

In summary, we have developed and experimentally validated a free-space and multichannel distributed gas sensing system based on the FMCW interferometry. The system successfully demonstrated simultaneous gas concentration measurement and spatial localization, achieving a ranging resolution of 2 mm and the detection sensitivity of 2 ppm·m. The comprehensive performance and scalability analysis presented in Section 4 confirmed the system's

accuracy, stability, and potential for practical deployment. Designed for cooperative retroreflectors, the architecture offers advantages including the high alignment tolerance and inherent robustness to slow platform motion. This work provided a promising solution for the high-precision and distributed gas sensing in the complex free-space environments, addressing the critical needs in industrial safety, environmental monitoring, and intelligent infrastructure management. The demonstrated combination of high positioning accuracy, sensitivity, and system scalability highlighted its potential for the deployment in the large-scale gas storage facilities, pipeline networks, and emission control zones. Although the current proof-of-concept setup introduced a limited amount of occlusion, the resulting blind region was very small and could be neglected at the present system scale. However, a linear arrangement of solid retroreflectors may enlarge such blind zones in the field deployments. In a static setup, arranging the retroreflectors with lateral offsets could effectively suppress shadowing, while the mounting retroreflectors on mobile platforms, such as the UAVs, might further reduce blind regions when the flexible coverage was required.

Future work will focus on the field deployment under diverse environmental conditions, incorporating adaptive signal processing and real-time control to enhance the system robustness and pave the way for the intelligent environmental monitoring networks.

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Declarations

Conflict of Interest Yongkang DONG is an editorial board member for Photonic Sensors and was not involved

in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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References

- [1] J. Zhao, Y. Tang, X. Zhu, and J. Zhu, "National environmental monitoring and local enforcement strategies," *Nature Cities*, 2025, 2(1): 58–69.
- [2] J. Wang, L. Feng, P. I. Palmer, Y. Liu, S. Fang, H. Bösch, *et al.*, "Large Chinese land carbon sink estimated from atmospheric carbon dioxide data," *Nature*, 2020, 586(7831): 720–723.
- [3] J. Jovanovic, M. Jovanovic, A. Jovanovic, and V. Marinovic, "Introduction of cleaner production in the tank farm of the Pancevo oil refinery, Serbia," *Journal of Cleaner Production*, 2010, 18(8): 791–798.
- [4] A. Fathy, Y. M. Sabry, I. W. Hunter, D. Khalil, and T. Bourouina, "Direct absorption and photoacoustic spectroscopy for gas sensing and analysis: a critical review," *Laser & Photonics Reviews*, 2022, 16(8): 2100556.
- [5] M. Gu, J. Chen, J. Mei, T. Tan, G. Wang, K. Liu, *et al.*, "Open-path anti-pollution multi-pass cell-based TDLAS sensor for the online measurement of atmospheric H₂O and CO₂ fluxes," *Optics Express*, 2022, 30(24): 43961–43972.
- [6] W. Zhou, Z. Cao, K. Zhao, Z. Wang, and L. Xu, "High-resolution TDLAS tomography of gaseous temperature and H₂O concentration in steady flames," *IEEE Transactions on Instrumentation and Measurement*, 2024, 73: 1–10.
- [7] X. Zhang, L. Xu, J. Wen, K. Zhao, and Z. Cao, "Robust temperature and gas concentration imaging by LAS tomography with adaptive basis function fitting and artifact removal," *IEEE Transactions on Instrumentation and Measurement*, 2024, 73: 1–11.
- [8] M. Li, L. Xu, and Z. Cao, "TDLAS tomography system for online imaging and dynamic process playback of temperature and gas mole fraction,"

- IEEE Transactions on Instrumentation and Measurement*, 2022, 71: 1–10.
- [9] Y. Hu, L. Xu, H. Xu, X. Shen, Y. Deng, H. Xu, *et al.*, “Three-dimensional reconstruction of a leaking gas cloud based on two scanning FTIR remote-sensing imaging systems,” *Optics Express*, 2022, 30(14): 25581–25596.
 - [10] T. D. Schmitt, J. Kuhn, R. Kleinschek, B. A. Loew, S. Schmitt, W. Cranton, *et al.*, “An open-path observatory for greenhouse gases based on near-infrared Fourier transform spectroscopy,” *Atmospheric Measurement Techniques*, 2023, 16(24): 6097–6110.
 - [11] J. J. Han, W. Zhong, R. C. Zhao, T. Zeng, M. Li, J. Lu, *et al.*, “Dual-comb spectroscopy over a 100 km open-air path,” *Nature Photonics*, 2024, 18(11): 1195–1202.
 - [12] K. C. Cossel, E. M. Waxman, F. R. Giorgetta, M. Cermak, I. R. Coddington, D. Hesselius, *et al.*, “Open-path dual-comb spectroscopy to an airborne retroreflector,” *Optica*, 2017, 4(7): 724–728.
 - [13] Q. F. Yang, Y. Hu, V. Torres-Company, and K. Vahala, “Efficient microresonator frequency combs,” *eLight*, 2024, 4: 18.
 - [14] S. Coburn, C. B. Alden, R. Wright, K. Cossel, E. Baumann, G.-W. Truong, *et al.*, “Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer,” *Optica*, 2018, 5(4): 320–327.
 - [15] B. C. Yao, W. T. Wang, Z. D. Xie, Q. Zhou, T. Tan, H. Zhou, *et al.*, “Interdisciplinary advances in microcombs: bridging physics and information technology,” *eLight*, 2024, 4: 19.
 - [16] C. B. Alden, S. C. Coburn, R. J. Wright, E. Baumann, K. Cossel, E. Perez, *et al.*, “Single-blind quantification of natural gas leaks from 1 km distance using frequency combs,” *Environmental Science & Technology*, 2019, 53(5): 2908–2917.
 - [17] G. B. Rieker, F. R. Giorgetta, W. C. Swann, J. Kofler, A. M. Zolot, L. C. Sinclair, *et al.*, “Frequency-comb-based remote sensing of greenhouse gases over kilometer air paths,” *Optica*, 2014, 1(5): 290–298.
 - [18] Y. W. Li, Y. C. Wang, Z. H. Liu, Y. H. Guo, X. Y. He, Y. Q. Zhao, *et al.*, “Gas mapping based-on dual microcomb driven nanomaterial functionalized fiber Bragg grating string,” *Photonix*, 2026, 7(1): 4.
 - [19] M. Shangguan, X. Guo, S. Lin, and Z. Lee, “Simultaneous column-averaged CO₂, temperature, and HDO measurement by absorption spectroscopy lidar: algorithm,” *IEEE Transactions on Geoscience and Remote Sensing*, 2024, 63: 1–12.
 - [20] J. Hamperl, J. B. Dherbecourt, M. Raybaut, J. Totems, P. Chazette, L. Régalia, *et al.*, “Range-resolved detection of boundary layer stable water vapor isotopologues using a ground-based 1.98 μm differential absorption LIDAR,” *Optics Express*, 2022, 30(26): 47199–47215.
 - [21] X. Guo, D. Wu, Z. Wang, B. Wang, C. Li, Q. Deng, *et al.*, “A review of atmospheric water vapor lidar calibration methods,” *Wiley Interdisciplinary Reviews: Water*, 2024, 11(3): e1712.
 - [22] A. Elkhazraji, M. Sait, and A. Farooq, “Integrated optical gas sensing and wireless communication in the mid-infrared,” *Applied Optics*, 2025, 64(16): D114–D121.
 - [23] M. Nikodem and G. Wysocki, “Chirped laser dispersion spectroscopy for remote open-path trace-gas sensing,” *Sensors*, 2012, 12(12): 16466–16481.
 - [24] A. Hangauer, Y. Chen, and G. Wysocki, “Chirped laser dispersion spectroscopy for spectroscopic chemical sensing with simultaneous range detection,” *Optics Letters*, 2021, 46(2): 198–201.
 - [25] A. Voss, E. Vanskä, D. Weidmann, A. Pulkkinen, and A. Seppänen, “Multi-open-path laser dispersion spectroscopy combined with Bayesian state estimation for localizing and quantifying methane emissions,” *Atmospheric Environment: X*, 2024, 22: 100260.
 - [26] Y. Chen, M. Soskind, J. McSpirt, J. Liu, R. Wang, N. Li, *et al.*, “Fugitive methane detection using open-path stand-off chirped laser dispersion spectroscopy,” *Optics Letters*, 2021, 46(13): 3005–3008.
 - [27] M. G. Soskind, N. P. Li, D. P. Moore, Y. Chen, L. P. Wendt, J. McSpirt, *et al.*, “Stationary and drone-assisted methane plume localization with dispersion spectroscopy,” *Remote Sensing of Environment*, 2023, 289: 113513.
 - [28] A. J. Hymans and J. Lait, “Analysis of a frequency-modulated continuous-wave ranging system,” *Proceedings of the IEE – Part B: Electronic and Communication Engineering*, 1960, 107(34): 365–372.
 - [29] X. Lou, C. Chen, Y. Feng, and Y. Dong, “Simultaneous measurement of gas absorption spectra and optical path lengths in a multipass cell by FMCW interferometry,” *Optics Letters*, 2018, 43(12): 2872–2875.
 - [30] X. Lou, Y. Feng, C. Chen, and Y. Dong, “Multi-point spectroscopic gas sensing based on coherent FMCW interferometry,” *Optics Express*, 2020, 28(6): 9014–9026.
 - [31] X. Lou, Y. Wang, N. Xu, and Y. Dong, “Gas sensing with 7-decade dynamic range by laser vector spectroscopy combining absorption and dispersion,” *Photonics Research*, 2023, 11(10): 1687–1693.
 - [32] X. Lou, Y. Wang, and Y. Dong, “Multipoint dispersion spectroscopic gas sensing by optical FMCW interferometry,” *Optics Letters*, 2021, 46(23): 5950–5953.
 - [33] L. Jia, X. Qu, and F. Zhang, “Frequency-modulated continuous-wave multiplexed gas sensing based on

- optical frequency comb calibration,” *Chinese Physics B*, 2024, 33(9): 094201.
- [34] X. Xiao, Z. Liu, H. Sun, Z. Wang, B. Duan, and W. Ren, “Neural network-enhanced FMCW gas spectroscopy,” *ACS Sensors*, 2025, 10(9): 6878–6886.
- [35] D. Tomaszewska, P. Jaworski, and M. Nikodem, “Frequency-multiplexed gas sensing using chirped laser molecular spectroscopy,” *Opto-Electronics Review*, 2018, 26(2): 103–107.
- [36] X. Lou, Y. Meng, N. Xu, and Y. Dong, “Rapid multipoint gas sensing using a silicon-photonic-integrated widely-tunable narrow-linewidth laser by FMCW interferometry,” *Journal of Lightwave Technology*, 2026, 44(12): 5280–5284.
- [37] P. Werle, “Accuracy and precision of laser spectrometers for trace gas sensing in the presence of optical fringes and atmospheric turbulence,” *Applied Physics B*, 2011, 102(2): 313–329.
- [38] L. Jia, B. Jin, J. Zheng, X. Qu, and F. Zhang, “Multichannel gas absorption spectrometer based on on-chip frequency-modulated continuous-wave interference system,” *Journal of Lightwave Technology*, 2024, 42(5): 1710–1715.