Cost-Effective Quasi-Parallel Sensing Instrumentation for Industrial Chemical Species Tomography

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Abstract—Chemical species tomography (CST) has been widely applied for the imaging of critical gas-phase parameters in industrial processes. To acquire high-fidelity images, CST is typically implemented by the line-of-sight wavelength modulation spectroscopy measurements from multiple laser beams. In this article, we present a novel quasi-parallel sensing technique and electronic circuits for industrial CST. Although the acquisition and processing of these multiple beams using a fully parallel data acquisition and signal processing system can achieve maximized temporal response in CST, it leads to a highly complex and power-consuming instrumentation with electronics-caused inconsistency between the sampled beams, in addition to a significant burden on data transfer infrastructure. To address these issues, the digitization and demodulation of the multibeam signals in the proposed quasi-parallel sensing technique are multiplexed over the high-frequency modulation within a wavelength scan. Our development not only maintains the temporal response of the fully parallel sensing scheme but also facilitates the cost-effective implementation of industrial CST with very low complexity and reduced load on data transfer compared with the fully parallel sensing technique. The proposed technique was analytically proved and then numerically examined by noise-contaminated CST simulations. Finally, the designed electronics was experimentally validated using a lab-scale CST system with 32 laser beams.

Index Terms—Chemical species tomography (CST), data acquisition (DAQ), digital lock-in (DLI), instrumentation, quasi-parallel, wavelength modulation spectroscopy (WMS).

I. INTRODUCTION

Industrial process tomography has been widely applied to image, qualitatively and/or quantitatively, the behavior of flows within processes in a nonintrusive manner. Various sensing modalities have been used, e.g., electrical tomography [1], [2], electromagnetic tomography [3], ultrasonic tomography [4], [5], x/γ-ray tomography [6], optical tomography [7], etc. Among these modalities, optical tomography utilizing chemical species-dependent photon absorption is named chemical species tomography (CST). Tunable diode laser absorption spectroscopy (TDLAS) is used in CST in a manner analogous to X-ray tomography with the difference that, for incident light at an appropriately selected wavelength, the absorption measurements enable the reconstruction of the unknown spatial distribution of the concentration of the target molecule [8]. Facilitated by the rapid technology development of the telecommunications industry, the past decade has witnessed accelerating advancement in the application of CST to solve industrial process engineering problems, e.g., vapor fuel imaging in internal combustion engines [9], [10], gas turbine exhaust imaging [11], [12], and power-plant boiler pollutant diagnosis [13].

Industrial CST is commonly implemented in harsh environments suffering from significant noise in the line-of-sight (LoS) TDLAS measurements [14]–[16], dozens of which are required in order to achieve adequate spatial resolution [17]. The major sources of noise include electronic noise, optical noise, and environmental noise [18], [19]. To achieve better noise rejection capability, calibration-free wavelength modulation spectroscopy (CF-WMS) is extensively adopted for implementing the LoS-TDLAS measurements in CST [20]–[24]. As shown in Fig. 1(a), a high-frequency modulation (typically 40–250 kHz) is added to a low-frequency wavelength scan (typically 1 Hz–10 kHz). The CF-WMS scheme raises the signal detection band to a designated frequency range and then extracts the nth harmonic signal by a demodulation process. Finally, path-integrated absorbances for all the laser beams are calculated from the first harmonic normalized nth harmonic signal, i.e., wavelength modulation spectroscopy (WMS) nf/f. In most cases, WMS-2f/f is favored due to its stronger intensity.

The hardware implementation of a data acquisition (DAQ) system for CF-WMS requires three basic elements.

1) High-speed digitization by an analog-to-digital converter (ADC) with adequate bandwidth for sampling the WMS-2f.
2) Digital lock-in (DLI) module for the simultaneous demodulation of WMS-2f and WMS-1f.
3) Real-time transferring of the sampled data to the high-level processors for continuous image reconstruction.

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To date, there are two typical sensing schemes to implement the CF-WMS method on all the laser beams for CST, i.e., fully parallel (FP) [11], [25] and time-division-multiplexing (TDM) [15], [26] sensing schemes.

As shown in Fig. 1(b), the FP sensing scheme detects simultaneously the laser transmission signals for all the laser beams by introducing an ADC and a DLI module for each beam. Although the FP sensing scheme can maximize the temporal resolution of the CST, its hardware implementation will inevitably lead to a highly complex, power-consuming, and expensive instrumentation system. Considering a CST system, typically, with more than 30 laser beams, the large number of signal amplifiers and ADCs inevitably cause some inconsistency between the sampled beams. In addition, the huge amount of spectral data sampled in parallel significantly burdens the data transfer in industrial applications [11] in which in situ signal digitization is generally located remotely from the high-level processors. In the case of on-board data storage, the sampled data will occupy the memory in a short period and, thus, hinder uninterrupted measurement.

Alternatively, the TDM sensing scheme, as shown in Fig. 1(c), simplifies the hardware by multiplexing the laser beams on the intervals of the neighboring wavelength scans. The selected laser beam with its transmission signal is digitized by the ADC and then demodulated. However, the temporal resolution of such a CST system is degraded by the sequential sampling. In the case of turbulent flow imaging, the TDM scheme will potentially lead to insufficient characterization of the instantaneous chemical reactions and heat transfer.

To address the above-mentioned challenges, we present here a quasi-parallel (QP) sensing technique and electronic circuits for industrial CST. The QP scheme is achieved by multiplexing the multibeam signals over the high-frequency modulation within a wavelength scan, enabling the digitization and demodulation of these beams with a single ADC and a single DLI module. The QP sensing scheme, initially addressed in [27], not only maintains the temporal response of the FP scheme but also facilitates the cost-effective implementation of industrial CST with very low complexity and reduced load on data transfer. In this article, we first illustrate the concept of the proposed scheme analytically. Then, numerical simulations are given to examine the performance of the proposed scheme with noise-contaminated CST measurements. With electronic circuits designed to utilize a commercial off-the-shelf field-programmable gate array (FPGA) platform, the QP sensing scheme was experimentally validated using a lab-scale CST system with 32 laser beams.

II. METHODOLOGY

A. Background of WMS

The fundamentals of CF-WMS have been well developed for noise-resistant gas measurement [20], [21]. To facilitate our presentation of the proposed WMS-based QP sensing scheme, the critical equations in terms of laser intensity modulation and frequency modulation in CF-WMS are reviewed. The time-varying diode laser output intensity $I(t)$ can be expressed as

$$I(t) = I_{0,s}(t) + I_{0,m}(t)$$

where the components $I_{0,s}(t)$ and $I_{0,m}(t)$ reflect, respectively, the injection current scan and current modulation at frequencies $f_s$ and $f_m$, given by (2) and (3), where the subscripts $s$ and $m$ refer to the scan and modulation, respectively.

$$I_{0,s}(t) = I_0 + \left[ \frac{1}{2} + i_{1,s}\cos(2\pi f_st + \phi_{1,s}) + i_{2,s}\cos(4\pi f_st + \phi_{2,s}) \right]$$

$$I_{0,m}(t) = \bar{I}_0 + \left[ \frac{1}{2} + i_{1,m}\cos(2\pi f_mt + \phi_{1,m}) + i_{2,m}\cos(4\pi f_mt + \phi_{2,m}) \right]$$

where $\bar{I}_0$ [V] is the average laser intensity, $i_1$ and $i_2$ are the amplitudes of the first- and second-order laser intensity modulation, respectively, and $\phi_1$ and $\phi_2$ are the phase shifts between the intensity modulation and frequency modulation for the linear and nonlinear components, respectively. Note that in (1), $I_0$ is counted twice; therefore, a factor of half has been introduced in (2) and (3) [21].

Accompanied by the intensity modulation, the output optical frequency of the laser $v(t)$ can be modeled by

$$v(t) = \bar{v} + v_s(t) + v_m(t)$$

where $\bar{v}$ is the center frequency, and $v_s(t)$ and $v_m(t)$ are the scanned and modulated frequencies, respectively. Similarly to $I_{0,s}(t)$ and $I_{0,m}(t)$, we express $v_s(t)$ and $v_m(t)$ as

$$v_s(t) = a_{1,s}\cos(2\pi f_st + \psi_{1,s}) + a_{2,s}\cos(4\pi f_st + \psi_{2,s})$$

$$v_m(t) = a_{1,m}\cos(2\pi f_mt + \psi_{1,m}) + a_{2,m}\cos(4\pi f_mt + \psi_{2,m})$$

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where the components $I_{0,s}(t)$ and $I_{0,m}(t)$ reflect, respectively, the injection current scan and current modulation at frequencies $f_s$ and $f_m$, given by (2) and (3), where the subscripts $s$ and $m$ refer to the scan and modulation, respectively.

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$$v_m(t) = a_{1,m}\cos(2\pi f_mt + \psi_{1,m}) + a_{2,m}\cos(4\pi f_mt + \psi_{2,m})$$
where \( a_1 \) and \( a_2 \) [cm\(^{-1}\)] are, respectively, the first- and second-order amplitudes, \( \psi_1 \) and \( \psi_2 \) are the first- and second-order phase shifts, respectively.

As shown in Fig. 1, the laser source is split into \( N \) beams that pass through the target gas sample. Denoting the absorbance of the \( i \)th laser beam by \( \alpha_i(v(t)) \) \((i = 1, 2, \ldots, N)\), the relationship between its incident intensity \( I_{0,i}(t) \) and transmitted intensity \( I_{t,i}(t) \) follows Beer–Lambert’s law and can be expressed by

\[
I_{t,i}(t) = I_{0,i}(t) e^{-\alpha_i(v(t))}.
\]

(7)

Assuming, for the purpose of illustrating the basic sensing requirement, that the gas properties are uniform along each laser beam, \( \alpha_i(v(t)) \) can be calculated by

\[
\alpha_i(v(t)) = L_i \phi(v(t)) P_i S(T) X_i
\]

(8)

where \( L_i \) [cm] is the path length of the \( i \)th laser beam through the subject, \( \phi(v) \) [cm] is the line-shape function, \( P_i \) [atm], \( X_i \), and \( T_i \) [K] are the pressure, molar fraction of the absorbing species, and temperature, respectively, and \( S(T) \) [cm\(^{-2}\)atm\(^{-1}\)] is the line strength of the selected absorption line. In CST, it is typical that \( X \) and \( T_i \) and sometimes \( P_i \) vary with position within the subject, and the aim of the technique is to recover the spatial distribution of \( X \) and/or \( T \). In this work, the spectral data have been obtained from HITRAN2016 [28].

### B. WMS-Based QP Sensing Scheme for CST

As shown in Fig. 2, \( I_{t,i}(t) \) from multiple beams are multiplexed within the wavelength scan at the resolution of the modulation period in the proposed QP sensing scheme. As a result, the multiplexed transmission signal \( I_{t,max}(t) \) sampled by a single ADC and further processed by a DLI module can be expressed as

\[
I_{t,max}(t) = I_{t,i}(t) \Big|_{t = j \times c/f_m}, \quad (j = 1, 2, \ldots) \quad (9)
\]

where \( j \) is the index of the multiplexing operation, and \( c \) is the number of modulation periods sampled per beam. In our implementation, (9) is implemented by using a fast analog \( 4 \times 1 \) multiplexer operating at \( cf_m \) between the neighboring beams. The index of the laser beam being sampled \( i \) is calculated by

\[
i = j - \lfloor (j - 1)/N \rfloor \times N \quad (10)
\]

where \( N \) is the total number of beams multiplexed over a wavelength scan. The operand \( \lfloor \cdot \rfloor \) is the floor function. For example, for four beams, and integer incrementing \( j \) in (10), we get \( i = 1, 2, 3, 4, 1, 2, 3, 4, \ldots \). As a result, \( I_{t,max}(t) \) contains the intermittent \( I_{t,i}(t) \) from all the \( N \) multiplexed laser beams within a wavelength scan. As the temporal resolution of a CST system depends on the frequency of the wavelength scan, the proposed QP sensing scheme can also maintain the maximum temporal resolution achieved using the FP sensing scheme, provided that all \( N \) beams are adequately sampled within a single wavelength scan. Fig. 2 explicitly illustrates the QP sensing scheme for \( c = 1 \) and \( N = 4 \).

To achieve the CF-WMS scheme, the WMS-1f and WMS-2f signals are extracted from the digitized \( I_{t,max}(d) \), denoted as \( I_{t,max}(d) \), using the DLI module. The in-phase and quadrature components of the WMS-1f, \( X_{1f,max} \), and \( Y_{1f,max} \), and WMS-2f, \( X_{2f,max} \), and \( Y_{2f,max} \) can be obtained by [29]

\[
X_{1f,max} = \sum_{d=0}^{D-1} I_{t,max}[d] \times R_{1,1f}[d] \quad (11)
\]

\[
Y_{1f,max} = \sum_{d=0}^{D-1} I_{t,max}[d] \times R_{Q,1f}[d] \quad (12)
\]

\[
X_{2f,max} = \sum_{d=0}^{D-1} I_{t,max}[d] \times R_{1,2f}[d] \quad (13)
\]

\[
Y_{2f,max} = \sum_{d=0}^{D-1} I_{t,max}[d] \times R_{Q,2f}[d] \quad (14)
\]

where \( R_{1,1f}[d] \) and \( R_{Q,1f}[d] \) (\( R_{1,2f}[d] \) and \( R_{Q,2f}[d] \)) are the sinusoidal reference signals with \( \pi/2 \) difference in phase at \( f_m \) (2\( f_m \)), respectively. The total number of digitized samples \( D = c \times f_m/d \), where \( d \) is the sampling frequency.

Similar to the demodulation of \( I_{t,max}(t) \), the nonabsorbing background signal \( I_{0,max}(t) \) is sampled and demodulated to obtain the absorption-free in-phase and quadrature components, \( X_{0f,max} \), \( Y_{0f,max} \), \( X_{2f,max} \), and \( Y_{2f,max} \), respectively. The multiplexed background subtracted WMS-2f/1f signal \( S_{2f/1f} \) is calculated as [22]

\[
m_{max}\quad S_{2f/1f} = \sqrt{\left( \frac{X_{2f,max}}{R_{1f,max}} - \frac{X_{0f,max}}{R_{1f,max}} \right)^2 + \left( \frac{Y_{2f,max}}{R_{1f,max}} - \frac{Y_{0f,max}}{R_{1f,max}} \right)^2} \quad (15)
\]

where

\[
R_{1f,max} = \sqrt{\left( \frac{X_{1f,max}}{R_{1f,max}} \right)^2 + \left( \frac{Y_{1f,max}}{R_{1f,max}} \right)^2} \quad (16)
\]
Each sample of $S_{2f/1f}$, as shown in Fig. 2, is demodulated from the accumulated $c$ modulation periods. As a result, the samples of $S_{2f/1f}$ from the multiplexed signal are obtained in sequence. For example, $S_{2f/1f}$ obtained in Fig. 2 contains the samples from the four multiplexed beams and can be expressed as

$$S_{2f/1f} = \{ \ldots \beta_1, \gamma_1, \delta_1, \varepsilon_1, \beta_2, \gamma_2, \delta_2, \varepsilon_2, \ldots \}$$

(18)

where $\beta_j$, $\gamma_j$, $\delta_j$, and $\varepsilon_j$ denote the samples of $S_{2f/1f}$ obtained from the four multiplexed laser beams with the $j$th multiplexing operation, respectively.

Then, the $S_{2f/1f}$ is demultiplexed to recover the $S_{2f/1f}$ spectrum for each beam, $S_{2f/1f,i}$ ($i = 1, 2, 3, 4$), as

$$S_{2f/1f,1} = \{ \ldots \beta_1, \beta_2, \ldots \}$$

(19)

$$S_{2f/1f,2} = \{ \ldots \gamma_1, \gamma_2, \ldots \}$$

(20)

$$S_{2f/1f,3} = \{ \ldots \delta_1, \delta_2, \ldots \}$$

(21)

$$S_{2f/1f,4} = \{ \ldots \varepsilon_1, \varepsilon_2, \ldots \}$$

(22)

It is worth mentioning that the multiply and accumulate (MAC) filter (11)–(14) is better suited for a discontinuously sampled signal, such as those resulting from the proposed QP scheme compared with the fast Fourier transform (FFT) method or other common filtering techniques, such as the infinite impulse response (IIR) filters. MAC filters can operate at the resolution of the modulation frequency. Therefore, a single MAC filter can be switched between different beams in runtime, unlike the FFT and IIR filters that rely on continuous signals.

### III. NUMERICAL SIMULATION

#### A. Simulation Setup

Numerical simulation was carried out to validate the proposed QP sensing scheme using the water absorption transition at 7185.6 cm$^{-1}$. Four laser beams were used in the simulation. Along the laser path with a length of 36 cm, temperature and pressure were assumed to be uniform at 293 K and 1 atm, respectively. The water concentrations on the four laser paths were assumed to be 0.8% (mole fraction), 0.7%, 0.6%, and 0.5%, respectively. The water is vapor mixed with air. $f_s$ and $f_m$ were set to 31.25 Hz and 62.5 kHz, respectively, i.e., $f_m = 2000 \times f_s$, ensuring that all beams could be sampled many times during the wavelength scan. $a_{1,s}$, $a_{1,m}$, $I_0$, $i_{1,s}$, and $i_{1,m}$ were set as 0.25 [cm$^{-1}$], 0.006 [cm$^{-1}$], 0.5 [V], 0.2, and 0.1, respectively. As the absorption feature is scanned twice within each sinusoidal scan, only the falling part of the scan is used in this work, as shown in Fig. 3. According to (9), the transmission signals, $I_{t,i}(t)$ ($i = 1, 2, 3, 4$), were multiplexed to obtain $I_{t,max}(t)$. By following the similar procedures, $I_{0,max}(t)$ was also obtained. Both $I_{t,max}(t)$ and $I_{0,max}(t)$ were digitized at a rate of $f_d = 15.625$ Mega Samples per second (MSps) with a single ADC and, subsequently, demodulated by a DLI module with $c = 2$ to obtain $S_{2f/1f}$.

![Fig. 3. Simulated raw transmitted signal for beam 1.](image)

![Fig. 4. For the four-beam simulated sensing using QP-WMS, (a) de-modulated $S_{2f/1f}$, and (b) demultiplexed $S_{2f/1f,i}$.](image)

| TABLE I |
| --- |
| **Comparison of the Temporal Resolution and Sampling Interval Among Different DAQ Schemes** |
| Sensing schemes | Temporal Resolution (frames per second, fps) | Sampling interval |
| --- | --- | --- |
| TDM | $f_c = 31.25$ Hz | $f_c = 31.25$ Hz | 32 ms |
| FP | $f_c = 31.25$ Hz | $f_c = 31.25$ Hz | 32 ms |
| QP | $f_c = 31.25$ Hz | $f_c = 31.25$ Hz | 32 ms |

As shown in Fig. 4(a), the demodulated $S_{2f/1f}$ contains 500 samples on the wavelength. Using (18)–(22), $S_{2f/1f,i}$ ($i = 1, 2, 3, 4$), each with 125 samples, as shown in Fig. 4(b), is obtained after the demultiplexing. The harmonic information for the four beams can be obtained using a single ADC-DLI pair with a sampling interval of 32 $\mu$s (4$f_m$c) between the neighboring beams. Therefore, the temporal response of the QP sensing scheme is much superior to the TDM scheme that samples the neighboring beams with a sampling interval of 32 ms (1$f_m$) with the same settings. Table I presents a comparison among the FP, TDM, and the proposed QP schemes in terms of temporal resolution and sampling interval between
the neighboring beams for scan frequencies $f_s$ of 31.25 and 125 Hz (keeping modulation frequency $f_m$ at 62.5 kHz). It can be seen that the temporal resolution of the QP scheme, such as that of the FP scheme, will always be $4 \times$ that of the TDM. Furthermore, the sampling interval of the QP scheme for neighboring beams is significantly less than the TDM, indicating its stronger representativeness of an FP system.

In comparison with the FP sensing scheme, the proposed QP scheme saves 75% hardware resources in terms of both the ADC-DLI pairs and memory space while maintaining the frame rate of the CST system, i.e., $f_s$. The reduced data throughput also alleviates the requirement placed on bandwidth, thus facilitating the remote data transfer in real time.

### B. Numerical Results and Discussions

The performance of the proposed QP sensing scheme is examined by considering the practical measurements in which the transmission for each laser beam is contaminated by various forms of noise. The sources of noise can be characterized by frequency-dependent noise and frequency-independent noise, respectively. The frequency-dependent noise mainly contains pink noise ($1/f$ noise), e.g., laser and detector excess noise, and low-frequency environmental noise generally caused by background scattering and flow-induced beam steering. The frequency-independent noise, which is known to have a white noise spectrum, is dominated by the thermal noise from the detector, signal amplification, and digitization circuits [18]. In the simulation, the signal-to-noise ratio (SNR) for the environmental noise was set to 15 dB lower with respect to $I_t$. As shown in Table II, this noise level was quantified by measuring the laser intensity fluctuation when a turbulent heated flow was imposed on a laser beam with stable intensity. To be specific, both the noise-free signal (without the turbulence) and the noise-contaminated signal (with the turbulence) were measured with the Red Pitaya (RP) ADC with a bandwidth of 40 MHz. Then, these signals were inputted into the MATLAB `snr` function to estimate the environmental noise. In addition, the combined pink and white noise was set to 56 dB lower with respect to $I_t$ in the simulation.

To validate the proposed scheme, $I_{t,i}(t)$ were demodulated and fitted by using both the QP and FP sensing schemes. As shown in Fig. 7(e)–(h) and (i)–(l), the

### Table II

| Component                  | SNR (dB) |
|----------------------------|----------|
| Photo-detector (G12182-003K, Hamamatsu) | 6.5e-13 W/Hz |
| Pre-amp (AD8033, Analog Devices)         | 11 nV/Hz |
| Mux (ADG704, Analog Devices)             | 82dB* |
| PGA (THS7002, Texas Instruments)         | 1.7 nV/Hz |
| Red Pitaya                             | 71.3 dB |

*due to cross talk noted in the datasheet.

### Fig. 6

Flowchart of the simulated implementation of the QP sensing scheme with sequentially introduced multiple sources of noise.
proposed QP scheme, with only one-quarter of the total number of samples in comparison with the FP sensing scheme, yields fitting results with similar residuals. To be quantitative and statistical, Table III presents the mean and standard deviation (std.) of the residual difference between the demodulated and fitted $S_{2f/1f,i}$ data for both the FP and QP sensing schemes using 500 repetitive simulations. Both the mean and std. values are very similar for both schemes with a maximum difference of 0.56% and 1.91%, respectively.

In comparison with the FP sensing scheme, the proposed QP scheme only generates one-quarter of the total number of samples, i.e., 500 samples per scan in FP versus 125 samples per scan in QP. However, the noise introduced by lower Nyquist frequency in the QP scheme can be mitigated by the spectral fitting process, yields fitting results with similar residuals, as shown in Fig. 7(e)–(h) and (i)–(l).

### IV. HARDWARE AND FIRMWARE IMPLEMENTATION

For hardware implementation of the QP sensing scheme, we designed a signal conditioning circuit (SCC), which consists of a 4-to-1 multiplexer (ADG704, analog devices) to produce the multiplexed transmission signal $I_{t,\text{mux}}(t)$ from the four laser beams, and a programmable gain amplifier (PGA) (THS7002, Texas Instruments) that further conditions the multiplexed signal. As shown in Fig. 8(a), the control bits for the SCC are derived from the digital inputs/outputs on a commercial off-the-shelf FPGA platform, the RP [31]. We used the STEMlab 125-14 kit. For more detailed specifications of STEMlab 125-14, refer to [31]. The analog output from the SCC is digitized by a 14-bit 125 MSps ADC that is integral to the RP.

The worst-case response time $t_{\text{mux}}$ of the ADG704 is 33 ns. To guarantee signal integrity, $t_{\text{mux}}$ must satisfy

$$t_{\text{mux}} < \frac{1}{f_d}. \quad (23)$$

That is to say, the multiplexed signal must be stabilized between the neighboring samples digitized by the ADC. As a result, the theoretical maximum sampling frequency $f_d$ supported in the design is 30.3 MHz. Its switching control is implemented by a multiplexer switching timing control (MSTC) logic. The MSTC synchronizes the switching operation of the multiplexer to the ADC by taking $c$, $f_d$, and $f_m$ into account, generating precisely timed logic signals that select the laser beam to be sampled per modulation period.

Subsequently, the digitized $I_{t,\text{mux}}(t)$ is demodulated by the DLI customized on the FPGA (Xilinx 7 series ZYNQ 7010) of the RP at the frequencies of $1f_m$ and $2f_m$. For each frequency, two 14-bit sinusoidal reference signals with a phase difference of 90° are generated using Xilinx’s direct digital synthesizer (DDS) IPs and then multiplied by the 14-bit digitized $I_{t,\text{mux}}(t)$. According to (11)–(14), the quadrature components, $X_{1f,\text{mux}}$ and $Y_{1f,\text{mux}}$,

| Beam | Parameter | FP | QP | Difference (%) |
|------|-----------|----|----|---------------|
| BM 1 | Mean (10³) | 6.2017 | 6.1988 | 0.0468 |
|      | Std. (10³)  | 2.3082 | 2.3046 | 0.1560 |
| BM 2 | Mean (10³) | 5.5534 | 5.5310 | 0.0403 |
|      | Std. (10³)  | 3.5778 | 3.5157 | 0.1757 |
| BM 3 | Mean (10³) | 4.8518 | 4.8280 | 0.4905 |
|      | Std. (10³)  | 3.4364 | 3.4686 | 0.9370 |
| BM 4 | Mean (10³) | 4.1496 | 4.1264 | 0.5591 |
|      | Std. (10³)  | 3.5033 | 3.4365 | 1.9068 |

Fig. 7. Implementation of both the FP and QP sensing schemes on the same laser transmission signals. (a)–(d) Simulated noise-contaminated transmission signals for the four laser beams. (e)–(h) and (i)–(l) De-modulated and fitted $S_{2f/1f,i}$ using the FP and QP sensing schemes, respectively.
and \(X_{2f,mux}\) and \(Y_{2f,mux}\), can be obtained by accumulating the 28-bit multiplied signals for \(c\) modulation periods. The accumulation process increases each quadrature component to \([28 + \log(c \times f_d / f_m)]\) bits. As a standard 32-bit embedded processor is used for data postprocessing and transfer, the shift operation, as shown in Fig. 8(a), is adopted to discard excess less significant bits. As a result, overflow can be avoided while maintaining minimal loss in precision. Finally, the quadrature components are transferred to the PC via Ethernet protocol.

As each RP is equipped with two simultaneous ADCs, the developed SCC and the DLI firmware are also duplicated, enabling two sets of four-beam QP sensing. Fig. 8(b) shows the hardware circuits, which enable a very compact implementation. The FPGA resources incurred by the QP sensing scheme in addition to the base firmware of RP are 1334 flip flops, 1456 lookup tables, 19 Block RAMs, and 8 DSPs.

V. EXPERIMENTS

A. Experimental Setup

To experimentally validate the proposed QP sensing system, a CST system with 32 laser beams was developed to image the two-dimensional (2-D) distribution of water vapor (\(H_2O\)) concentration. As each measurement hub [see Fig. 9(a)] is capable of measuring eight beams with the QP sensing scheme, as discussed above and shown in Fig. 8, four hubs were utilized. A distributed feedback laser diode (NLK1E5GAAA, NTT Electronics) working at 7185.6 cm\(^{-1}\) was used for \(H_2O\) sensing in the experiment reported here. The laser was fed with a signal consisting of a scan sinusoid at \(f_s = 31.25\) Hz and modulation sinusoid at \(f_m = 62.5\) kHz from an arbitrary signal generator (ASG). Using a 32-way fiber splitter, the output laser from the pigtailed laser diode was equally split into 32 channels, each collimated by a fiber collimator (CFC5-C, Thorlabs) for launch across the subject. As shown in Fig. 9(a), the 32 laser beams were arranged in four equiangular projections (45°) with eight parallel beams in each projection. The neighboring beam spacing \(d\) is 1.8 cm, while the distance \(D\) between the emitter and detector of each beam is 36.76 cm. Each transmitted laser beam was incident on a dedicated photodetector (G12182-003K, Hamamatsu). The 32 transmission signals were processed in QP mode with a dedicated hub for each group of eight signals, multiplexing four signals to each ADC sampling at 15.625 MSps. With \(c = 2\), a
total of 500 samples were accumulated for each DLI operation to obtain 1000 wavelength samples in $S_{2f/1f,i}$ per frame on each hub. Finally, signals were demultiplexed to obtain $S_{2f/1f,i}$ for all 32 beams, leading to 125 wavelength points in falling and rising part of the scan, respectively. The DAQ was synchronized to the laser driver by means of a trigger generated by the ASG at $f_s$. Data transfer to a remote PC from the four hubs was achieved using an Ethernet switch (GO-SW-5G, D-link), enabling the transfer of $4000 \times 32$ bits per hub per frame. The tomographic frame rate was 31.25 fps.

B. Experimental Results and Discussion

To examine the noise performance of the developed electronics, the $S_{2f/1f,i}$ ($i = 1, 2, 3, 4$) were measured using a single DAQ channel for 100 times in room air without any artificially generated $H_2O$ absorption. The mole fraction of water was 0.0135. In this case, there is no flow-induced uncertainty imposed on the laser beams. As shown in Fig. 10, each $S_{2f/1f,i}$ contains 125 wavelength samples with the proposed QP sensing scheme. Fig. 10 shows the mean value of each $S_{2f/1f,i}$, while the error bars show the standard deviation. As the temperature, $H_2O$ concentration, and path length are the same for the four laser beams, the peak values of the sampled $S_{2f/1f,i}$ ($i = 1, 2, 3, 4$) are very close, with a maximum difference of 2.3%. The maximum standard deviation of $S_{2f/1f,i}$ observed for any of the four beams is 0.0052, demonstrating excellent noise suppression by the developed QP sensing instrumentation.

A phantom (i.e., known) 2-D $H_2O$ vapor distribution was generated using a container filled with hot water and the measurement plane placed vertically above it, in a simple proof-of-concept experiment. As shown in Fig. 9(b), the container was placed at the center of the region of interest. Fig. 11 shows the sampled and fitted $S_{2f/1f,i}$ from the same four laser beams for a single frame of data. Stronger absorption can be observed for beams 3 and 4 due to their penetration of the evaporated $H_2O$ with a longer path length. To reconstruct the 2-D distribution of $H_2O$ concentration, the path-integrated absorbances from the 32 laser beams were calculated from the fitting results.

Fig. 11. Spectral fitting of the experimental signals. (a)–(d) Demodulated and fitted $S_{2f/1f,i}$ from the same four laser beams for a single frame of data using the QP sensing schemes.

Fig. 12. Reconstructed 2-D distribution of $H_2O$ concentration using the developed QP sensing scheme and instrumentation.

VI. CONCLUSION

In this article, we introduced a cost-effective QP sensing technique and instrumentation developed for the industrial application of CST. The new development implemented, for the first
time, the multiplexing of multibeam transmission signals over the high-frequency modulation within each wavelength scan, followed by digitization and demodulation. Consequently, it significantly reduced the hardware/software complexity of CST system with 32 laser beams was set up to experimentally validate the proposed scheme. The experimental results further demonstrated that high-fidelity harmonic signals can be obtained using the proposed QP sensing scheme. Finally, the path-integrated absorbances extracted from the harmonic signals were used to reconstruct a 2-D distribution of H₂O concentration, demonstrating the effectiveness the developed technology and instrument.

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