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ABSTRACT

The present paper describes a system and method for indirect emission spectroscopy of CO₂ in the visible spectrum. This is achieved by using a microplasma spectrometer that first converts CO₂ into CO and then measures emissions from the CO Ångström system \((B^1\Sigma^+ \rightarrow A^1\Pi)\) at 560 nm. The experiments were performed on gaseous samples of CO₂, mixed in both N₂ and air, to concentrations between 0.01% and 100%. In addition to the microplasma spectrometer, the process was monitored by mass spectrometry with a residual gas analyzer. The CO₂ to CO conversion efficiency was found to be very high, reaching a maximum of 41% at close to 100% selectivity. Furthermore, the CO Ångström system was shown to facilitate excellent spectroscopic measurement of CO₂ concentrations below 10%, with a linearity of \(R^2 > 0.99\) and an expected limit of detection in the parts-per-thousands range. The most promising aspect of the results was that the analysis was performed on extremely small total sample amounts where the gas flow through the systems was in the 0.1 μmole/s range. Hence, the present system has the prospect of filling a void in current sensor technology, where inexpensive and easy-to-use optical systems, such as nondispersive infrared sensors, cannot handle small sample amounts, while mass spectrometers, which can handle such samples, still are expensive, complex, and bulky.

INTRODUCTION

Carbon dioxide is probably the most common sample molecule in gas spectroscopy with applications spanning from regulating ventilation systems and tracking industrial processes to environmental monitoring or even space science. The most common sensors are based on nondispersive infrared (NDIR) spectroscopy and can easily and accurately detect and quantify CO₂ down toward a few ppm. More precise optical instruments based on, e.g., cavity ringdown spectroscopy or off-axis integrated cavity output spectroscopy can reduce the limit of detection orders of magnitude more.

Although most of these sensors strive toward minimizing dead volumes, they all require fairly large total sample amounts to perform an accurate analysis. Hence, in applications where the total sample amount is inherently limited, e.g., when analyzing single cells or rare isotopes, other methodology and technology are required. Traditionally, mass spectrometry has been used, even though it lacks the simplicity of the optical methods, particularly due to the need for high-vacuum systems.

In this context, spectroscopic methods based on microplasma technology can offer an advantage, since they have the capability of combining the simplicity of the optical sensors with the small sample processing of the mass spectrometers thanks to their minute internal volume. We have previously investigated one such method called optogalvanic spectroscopy, which proved to be extremely effective with respect to both minimum detectable absorption and noise equivalent absorption sensitivity and capable of handling samples in the subnanogram range. However, optogalvanic spectroscopy relies on IR lasers that are both complex and expensive.

An alternative method could be emission spectroscopy, where different species can be detected and quantified by analyzing the...
radiation that is emitted from the plasma. In such a system, the emitted radiation is dispersed on a grating or in a prism, and the individual intensities of the diffracted or refracted wavelengths are analyzed by a photodetector array. From an experimental point of view, the best wavelengths for such an analysis are in the mid- and far-IR regime, where CO₂ exhibits ro-vibrational transitions with good selectivity toward other common species. However, this wavelength regime is challenging from a technical point of view, where, particularly, the detector starts to become a problem, since high density IR photodetector arrays are still expensive and complex to fabricate and employ.10,11 In the visible wavelength regime, on the other hand, there is an abundance of high-performance inexpensive photodetectors as a result of the last decade’s immense development in digital camera technology. However, here, CO₂ lacks useful emissions.

In this paper, we investigate a way of circumventing these challenges and facilitate CO₂ emission spectroscopy in the visible wavelength regime. To achieve this, we rely on another property of the plasma, namely, its chemical reactivity, particularly its ability to dissociate CO₂ molecules into CO — that happen to have several useful transitions at visible wavelengths.12 We have focused on the so-called Ångström system (\(B^1Σ^+ \rightarrow Λ^1Π\)) that was first observed by Anders Ångström — the namesake of our laboratory — in 187513 and exhibits strong emission bands between 450 and 650 nm.14 In order to evaluate the usefulness of the proposed method for CO₂ spectrometry, we investigate the ability of the plasma to reliably convert CO₂ to CO using a residual gas analyzer (RGA) and the applicability of the CO Ångström system to emission spectroscopy using a microplasma emission spectrometer.

**MATERIALS AND METHODS**

The measurement system, Fig. 1, was based on a microplasma emission spectrometer (Pithos, Fourth State Systems AB, Sweden) containing a stripline split-ring resonator microplasma source\(^\text{15}\) with an operating pressure between 0.075 and 7.5 Torr and a CCD spectrometer with a bandwidth of 200–1000 nm, a FWHM of 2 nm at 633 nm, a 20 μm by 2 mm slit, and a 600 lines/mm and 800 nm blaze grating. The microplasma source was fed with a sample gas though a 190 mm long and 40 μm diameter capillary, from a reference gas volume consisting of a 100 ml vial with a 23 G cannula that was filled with different mixtures of CO₂, N₂, and air. The outlet of the spectrometer was connected to a 170 l/s turbo vacuum pump (TCP 300, Pfeiffer Balzers, Germany) creating a net sample flow of about 0.1 μmol/s through the system.

The fluidic outlet of the spectrometer was also connected to the inlet of a residual gas analyzer (Model XT100, Extorr Inc., PA, USA) though another capillary, this time 320 μm in diameter and 400 mm long. The purpose of both capillaries was to reduce the pressure, first from atmosphere to 0.75 Torr inside the spectrometer and then from 0.75 to <10⁻⁶ Torr in the RGA. The latter two pressures were monitored by separate gauges (AMS-5915, Analog Microelectronics, Germany and PKR250, Pfeiffer Balzers, Germany). In the experiments, the RGA was used to monitor the partial pressure of three molecular masses, \(M_i\) that corresponded to N₂ and CO, O₂, and CO₂, i.e., \(M = 28, 32, \text{and } 44\).

Finally, the microplasma source, spectrometer, and RGA were connected to a computer (Yoga 530, Lenovo, China) to control the pressure and power in the former and record the outputs of the two latter. These outputs were then postprocessed as described below.

A total of 27 different samples were analyzed in the study (Table I). First, N₂ was mixed with CO₂ in 10% steps from 0% to 100%. The mixing was performed in the vials using their incorporated volume grading. Before mixing, the vial was rinsed with pure N₂, by filling and emptying it thrice. Then, the vial was filled with 100 ml of the minority species and emptied to the correct volume fraction. Finally, the vial was filled with the majority species up to 100 ml. Throughout filling and handling, the vials were fitted with a 600 μm diameter cannula through which the inlet capillary of the microplasma emission spectrometer could be inserted. The small cross section of the cannula and large volume of the vial limited diffusion and stabilized the concentration of the reference gas within ± 1% over time spans relevant to the experiment. In addition to N₂, CO₂ was mixed with air sampled from the laboratory to investigate how the plasma chemistry of a more complex gas mixture affected the results. Finally, experiments with low concentrations of CO₂ in N₂ were performed to probe limits of detection and quantification. These samples were diluted from starting points of 10% and 50% CO₂ by emptying the vial to 10 ml and refilling it with N₂ to 100 ml until the desired fraction was reached. Due to repeated mixing, the composition of these samples suffered from a higher degree of uncertainty.

The spectroscopy and RGA measurements were performed in parallel beginning with a 20 s RGA analysis of the gas composition of the sample without plasma. Then, the plasma was ignited at a power, \(P\), of about 38 dBm, after which both the spectroscopic and RGA signals were recorded while decreasing the power in six steps (37, 36, 34, 28, and 23 dBm). Below the last step, the plasma went out. The dwell time at each power step was 20 s for samples 1–21 and 40 s for samples 22–27. Moreover, the integration time of the CCD spectrometer was 0.10 s for samples 1–21 and 0.15 s for samples 22–27. The corresponding change in the intensity was linear with respect to integration time.

The sampling frequency of the spectrometer and the RGA were slightly different (0.2–1 s for the spectrometer and 3.7 s for

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**FIG. 1.** Schematics of the experimental setup, showing fluidic, data, and optical connections.
the RGA). Moreover, the response of the RGA was slightly delayed with respect to the plasma due to column effects in the interconnecting capillary. Hence, the results were interpolated to a common frequency in the postprocessing. In order to synchronize the measurements, the times when the plasma went on and off—an effect that was clearly visible in both signals—were measured manually and used as calibration points.

RESULTS AND DISCUSSION

Figure 2 shows typical spectra for pure CO₂ (sample 1) as well as pure N₂ (sample 11). As can be seen, the Ångström system of CO was clearly visible with distinct emissions from five bands corresponding to \( \nu = 0-4 \) between 440 and 610 nm. Furthermore, N₂ showed limited background at these wavelengths, which is advantageous from a spectroscopy point of view.

Figure 3 shows two of the Ångström bands—at 520 and 560 nm—in more detail. More thorough analysis of the N₂ background showed that the 520 nm band (\( \nu = 2 \)) was generally stronger but also perturbed by an N₂ band at 518 nm. The 560 nm band, on the other hand, had a more predictable background. Hence, it was used for the subsequent spectrometric calculations despite its lower brightness. The spectroscopic CO signal of the 560 nm band, \( I_{CO} \), was calculated in three steps, where (1) the spectrum was filtered

| Sample | CO₂  | N₂   | Air |
|--------|------|------|-----|
| 1      | 1.0  | 0    | 0   |
| 2      | 0.9  | 0.1  | 0   |
| 3      | 0.8  | 0.2  | 0   |
| 4      | 0.7  | 0.3  | 0   |
| 5      | 0.6  | 0.4  | 0   |
| 6      | 0.5  | 0.5  | 0   |
| 7      | 0.4  | 0.6  | 0   |
| 8      | 0.3  | 0.7  | 0   |
| 9      | 0.2  | 0.8  | 0   |
| 10     | 0.1  | 0.9  | 0   |
| 11     | 0    | 1.0  | 0   |
| 12     | 0    | 0    | 1.0 |
| 13     | 0.1  | 0    | 0.9 |
| 14     | 0.2  | 0    | 0.8 |
| 15     | 0.3  | 0    | 0.7 |
| 16     | 0.4  | 0    | 0.6 |
| 17     | 0.5  | 0    | 0.5 |
| 18     | 0.6  | 0    | 0.4 |
| 19     | 0.7  | 0    | 0.3 |
| 20     | 0.8  | 0    | 0.2 |
| 21     | 0.9  | 0    | 0.1 |
| 22     | \( 5 \times 10^{-2} \) | 0.95 | 0   |
| 23     | \( 1 \times 10^{-2} \) | 0.99 | 0   |
| 24     | \( 5 \times 10^{-3} \) | \( >0.99 \) | 0   |
| 25     | \( 1 \times 10^{-3} \) | \( >0.99 \) | 0   |
| 26     | \( 5 \times 10^{-4} \) | \( >0.99 \) | 0   |
| 27     | \( 1 \times 10^{-4} \) | \( >0.99 \) | 0   |

![FIG. 2. Typical spectra of pure CO₂ and N₂. The CO Ångström system with bands corresponding to \( \nu \) between 0 and 4 are marked in the figure.](image)

![FIG. 3. Close-up of the (0-2) and (0-3) bands of the Ångström system at descending carbon dioxide concentration.](image)
with respect to both wavelength and time with smoothing average filters of power 2 and 7, respectively. (2) The background was subtracted by fitting a fourth order Gaussian to the spectrum in the wavelength interval $\lambda = 552$–$564$ nm, but excluding points between $\lambda = 558$ and $562$ nm. (3) Finally, $I_{CO}$ was calculated as the integral of the latter interval. The lower inset of Fig. 10 visualizes these calculations in more detail.

Figure 4 shows typical RGA measurements at varying plasma power. These were subject to several background effects primarily stemming from leaks in the setup and overlapping molecular masses. Looking at Fig. 4, it appears that the partial pressure, $p$, of CO$_2$ and CO in sample 1 (100% CO$_2$) was about the same before igniting the plasma and that the CO pressure then increased at increasing power with a corresponding reduction of CO$_2$. However, CO has the same molecular mass as N$_2$, $M = 28$, which was the major leak species. Moreover, the measurement of sample 11 (100% N$_2$) showed that the N$_2$ pressure was more or less unaffected by the plasma. Hence, it was reasonable to assume that $p_{CO} + p_{N_2}$ of sample 1 before plasma ignition was purely due to background N$_2$ and that the change in pressure after plasma ignition was purely due to CO. Furthermore, sample 11 showed a slight background of CO$_2$, which, again, was assumed to be due to background effects. Hence, $p_{CO}$ of sample 11 was subtracted from all $p_{CO_2}$ measurements to get accurate results. Similarly, $p_{CO} + p_{N_2}$ before plasma ignition of sample 1 was subtracted from all measured N$_2$ pressures.

Applying these adjustments to all 66 measurement points of samples 1–11 and adding the resulting partial pressures of CO$_2$, CO, and N$_2$, the total pressure stemming from the plasma became $p_{Tot} = 0.47 \pm 0.01$ μTorr, where the very small standard deviation strongly indicated that the background subtraction method was viable. Examples of adjusted RGA measurements can be seen in Fig. 5.

Figure 5 shows the combined results of all measurements. The different panels depict the dependencies of the investigated partial pressures, $p_{CO}$ and $p_{CO_2}$, and the spectroscopic signal, $I_{CO}$, with respect to power and CO$_2$ sample concentration. Here, some general trends can be observed where, e.g., the plasma’s efficiency to dissociate CO$_2$ into CO was the greatest for low CO$_2$ concentrations and high power.

In fact, the plasma was generally effective in converting CO$_2$ into CO, with maximum, average, and minimum conversion efficiencies, $Y = \frac{p_{CO} - p_{CO}(P < 20 \text{ dBm})}{p_{CO_2}(P < 20 \text{ dBm})}$, of 41%, 28%, and 5.3%, for samples mixed in N$_2$, and 35%, 25%, and 5.1%, for samples mixed in air. Moreover, the selectivity of the conversion, i.e., the fraction of CO$_2$ that was converted to CO, $S = \frac{p_{CO} - p_{CO}(P < 20 \text{ dBm})}{p_{CO_2}(P < 20 \text{ dBm})}$, was equally high with $S = 100 \pm 3.5\%$ for samples mixed in N$_2$ and $S = 91 \pm 1.6\%$ for samples mixed in air.

CO$_2$ to CO conversion is a scientific field of its own, since it constitutes a promising reaction in artificial photosynthesis, and the produced CO is an important part of syngas that, in turn, can be used to produce an abundance of different hydrocarbons.$^{16–18}$ Generally, conversion efficiencies of $Y > 20\%$ are regarded as very promising, particularly if they are combined with high selectivity.$^{19}$ This would put the present system in a very promising position. However, the overall energy efficiency, i.e., the supplied plasma power per converted molecule, was rather low (<1%), primarily due
to the very low gas flow through the system. Here, it should be pointed out that the current flow rate was intentionally low, since the proposed system and method were intended for applications where the total available sample amount is inherently limited. The current flow rate was chosen to have a good coupling to the RGA, while the spectrometer worked well with both an order of magnitude higher and lower flows. Nonetheless, additional investigations of the conversion efficiency at higher flow rates should be performed to evaluate the system potential as a CO\textsubscript{2} to CO converter. Such experiments are currently under way in our laboratory.

The samples mixed with air showed slightly lower CO\textsubscript{2} and CO concentrations after passing the plasma than those mixed with N\textsubscript{2}. This was likely due to the more diverse nature of the air samples, where particularly the presence of O\textsubscript{2} allowed for more complex chemistry. However, both contents were only shifted by a constant factor going from N\textsubscript{2} to air as shown in Fig. 7. Hence, this effect had no impact on the spectrometric usefulness of the systems.

Another distinct feature was the saturating behavior of the CO production rate at high CO\textsubscript{2} concentrations. Figure 8 shows $P_{\text{CO}}$ at different CO\textsubscript{2} sample concentrations for two different powers. As can be seen, the CO production rate started to saturate at CO\textsubscript{2} concentrations higher than $\sim$50%. This saturation behavior could

![FIG. 6. Partial pressures of CO\textsubscript{2} (a) and CO (b), $P_{\text{CO}}$ and $P_{\text{CO}}$, as functions of plasma power, $P$, and CO\textsubscript{2} concentration. The resulting relative amount of produced CO is shown in (c), while (d) shows the emission intensity of the (0–3) Ångström band of CO, $I_{\text{CO}}$, under the same conditions.]

![FIG. 7. Relative content of CO\textsubscript{2} and CO in the samples mixed with N\textsubscript{2} (samples 1–11) and air (samples 12–21) at constant power, as measured by the RGA.]

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be mitigated by mixing the CO₂ in air instead of N₂, which suggested that the cause of the saturation likely was due to the plasma chemistry, where the presence of N₂ affected reaction time constants that promoted CO production, and the presence, or lack, of O₂ and/or other oxygen species confined the amount of CO produced. Moreover, the saturation behavior could also be mitigated by increasing the power, where the amount of produced CO was more or less linear with respect to supplied power at high CO₂ concentrations as can be seen from the inset of Fig. 8, although it should be pointed out that the power was measured in dBm and not watts.

A similar saturation was observed in the emission intensity of the (0–3) Ångström band of CO, I_{CO}, as seen in Fig. 9. The fact that the relationship between I_{CO} and p_{CO} was close to linear, the inset of Fig. 9, suggested that the cause of the saturation was the same as for the CO production. Moreover, increasing the power
increased the dynamic range of the measurement from 0% to 50% CO₂, at \( P = 28 \text{ dBm} \) up to 0%–80% at \( P = 37 \text{ dBm} \), defining the dynamic range as the linear regime with \( R^2 > 0.95 \).

**Figure 10** shows the combined data of samples 1–11 and 22–27, which exhibited a linear dependence on the CO₂ concentrations up to concentrations of 10% after which the dependence became exponentially decreasing. Hence, despite the mitigations addressed above, the proposed spectrometric method cannot be regarded as promising for measuring high concentrations of CO₂. At lower concentrations, on the other hand, the measurement showed a close to linear relationship to the CO₂ concentration with \( R^2 > 0.99 \) (Fig. 10). These results should still be regarded as preliminary but suggest that the method is currently capable for measuring CO₂ concentrations down toward the part-per-thousands range. However, it is also clear that, even though the precision is good, the accuracy has to be improved.

Further studies of the limit of detection of the method should be performed on premixed standard samples, since the mixing process used in this paper started to become increasingly inaccurate below concentrations of \( \sim 1\% \). Moreover, more complex sample compositions than CO₂ in N₂ should be investigated in more detail to see how they affect the accuracy of the measurement. Still, it should be pointed out that the analysis in this paper was based on only one emission band in a vast spectrum—the inset of Fig. 10 shows in more detail how \( f_{\text{CO}_2} \) was calculated. In fact, we are currently using only about 1.5% of the collected spectrometric data. Hence, we believe that more complex postprocessing has that potential of improving the limits of detection and quantification several orders of magnitude and intend to investigate this by using methods for multivariate data analysis and machine learning.

Finally, it should be pointed out that the present system and method suffer from some inherent limitations of its own. Particularly, it cannot distinguish CO converted from CO₂ from CO that was already in the sample before the conversion. Hence, it requires some postulated knowledge of the sample composition. Still, most potential applications, e.g., studies of metabolism in small cell cultures, or rare isotope ratios, fulfill this postulate; therefore, the proposed system should be of interest to the scientific community despite this limitation. Moreover, the operating pressure of the microplasma source requires the system to have a pump, making it more complex than, e.g., diffusion based NDIR spectroscopy systems. Still, it requires a much less complex pump than a mass spectrometer. In the present study, the microplasma source was pumped with the rough pump of the RGA turbo-pump system. It is also possible to increase the operating pressure of the plasma up to 75 Torr by changing its geometry. This would enable the use of much simpler pumps, e.g., membrane pumps. However, increasing the operating pressure to these levels will likely also affect the spectroscopic properties of the plasma. Hence, an investigation of the effects of increased pressure on the results reported in this study is currently under way in our laboratory.

**CONCLUSION**

A spectrometric method to indirectly detect and quantify CO₂ in the visual spectrum by utilizing emissions of dissociated CO in a microplasma was studied and found to be useful, particularly for CO₂ concentrations between 0.1% and 10%. The CO₂ to CO conversion efficiency of the system was very high, reaching above 40% with selectivities close to 100%. Furthermore, the (0–3) Ångström band of CO was shown to facilitate spectroscopic measurement with high precision and linearity over the full investigated range for CO and below concentrations of 10% for CO₂. Achieving such performance at sample flow rates in the 0.1 μmol/s regime suggests that, even though the investigated system and method could not compete with, e.g., NDIR spectroscopy in large scale applications, it has great potential to become useful when the total available sample amount is inherently limited.

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**REFERENCES**

1. J. Kwon, G. Ahn, G. Kim, J. C. Kim, and H. Kim, in 2009 ICCAS-SICE (IEEE, 2009), pp. 1683–1687.
2. S. Neethirajan, D. S. Jayas, and S. Sadistap, Food Bioprocess Technol. 2, 115 (2009).
3. D. Bastviken, I. Sundgren, S. Natchimuthu, H. Reyier, and M. Gålfalk, Biogeosciences 12, 3849 (2015).
4. C. R. Webster, P. R. Mahaffy, G. J. Flesch, P. B. Niles, J. H. Jones, L. A. Leshin, S. K. Atreya, J. C. Stern, L. E. Christensen, T. Owen, H. Franz, R. O. Pepin, A. Steele, and MSL Science Team, Science 341, 260 (2013).
5. T. Yasuda, S. Yonemura, and A. Tani, Sensors 12, C1 (2012).
6. F. R. Vogel, L. Huang, D. Ernst, L. Giroux, S. Racki, and D. E. J. Worlthy, Atmos. Meas. Tech. 6, 301 (2013).
7. B. Paul, L. Lapson, and J. G. Anderson, Appl. Opt. 40, 4904 (2001).
8. M. Berglund, G. Thornell, and A. Persson, J. Appl. Phys. 114, 033302 (2013).
9. A. Persson and M. Berglund, Laser Phys. Lett. 13, 075703 (2016).
10. A. Rogalski, J. Antoszewski, and L. Faraone, J. Appl. Phys. 105, 091101 (2009).
11. Y. Liu, N. Wei, Q. Zeng, J. Han, H. Huang, D. Zhong, F. Wang, L. Ding, J. Xia, H. Xu, Z. Ma, S. Qiu, Q. Li, X. Liang, Z. Zhang, S. Wang, and L.-M. Peng, Adv. Opt. Mater. 4, 238 (2016).
12. Y. Itikawa, J. Phys. Chem. Ref. Data 31, 749 (2002).
13. A. Ångström and L. Thalen, Nova Acta Regiae Soc. Sci. Ups. 9, 1–34 (1875).
14. C. Le Floch and C. Amon, Chem. Phys. 97, 379 (1985).
15. M. Berglund, M. Grudén, G. Thornell, and A. Persson, Plasma Sources Sci. Technol. 22, 055017 (2013).
16. X. Liu, C. Kunkel, P. Ramírez de la Piscina, N. Hom, F. Viñes, and F. Illas, ACS Catal. 7, 4323 (2017).
17. M. D. Porosoff, S. Kattel, W. Li, P. Liu, and J. G. Chen, Chem. Commun. 51, 6988 (2015).
18. K. Zhang, G. Zhang, X. Liu, A. N. Phan, and K. Luo, Ind. Eng. Chem. Res. 56, 3204 (2017).
19. C. Chen, L. Wang, T. Godfroid, and R. Snyders, Plasma Chemistry and Gas Conversion (IntechOpen, 2018), pp. 59–69.