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Phasor representation for the nonlinear photoacoustic signal

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Abstract

In CO₂ laser-based photoacoustic (PA) systems, N₂ takes part in the generation of the PA signal. This process causes the nonlinear relation of the photoacoustic signal to the CO₂ concentration. This phenomenon can be explained simply using a phasor diagram. The model leads to the determination of the lag in the PA signal due to CO₂ relaxation.

Keywords: photoacoustic, phasor, nonlinear

1. Introduction

In past years, photoacoustic (PA) phenomena have been investigated and explored extensively. As photoacoustics can be generated in a simple and easy way, its applications can be found in many fields of research [1–6]. Within infrared spectroscopy, photoacoustics is used for the detection of greenhouse gases. Molecular gases, such as CO₂ and H₂O, absorb infrared radiation, while the main constituents of air—N₂ and O₂—do not [7]. The strength of a PA signal depends on the absorption coefficient of the gas at a specific infrared wavelength, the number of absorbing molecules (i.e. the gas concentration) and the laser power. When multicomponent gas mixtures are used with spectral interference, individual gases contribute to the total PA signal [8]. Photoacoustic generation in gas spectroscopy can be explained as follows: infrared laser radiation is absorbed by the gas sample, and the excited molecules are de-excited via collisions generating heat within a closed volume, causing a pressure increase. Modulating the laser power at a specific audio frequency causes pressure fluctuations, or a sound, at that frequency.

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CO₂ laser-based photoacoustic spectroscopy is well known to be a powerful tool for measuring low concentrations of gases with high sensitivity down to the ppbv level (ppbv, parts per billion volume mixing, 1:10⁹) [6]. Nevertheless, special conditions should be considered if the sample also contains CO₂ and N₂ gas. In contrast to what was published by Fukuhara *et al* [7], N₂ takes part in the generation of the PA signal. In the latter case, kinetic cooling causes the PA signal to lag in phase when applying laser amplitude modulation. In specific conditions, the amplitude of the PA signal decreases instead of increasing with the increasing CO₂ concentration [9–11]; this behaviour has been modelled in detail and is used for measuring ammonia [10] and ethylene [11] in mixtures of H₂O, CO₂ and N₂.

To model this for pedagogical purposes we use a superposition of two waves with the same frequency but a different phase. Now, with a simple basic calculation, the role of N₂ on the CO₂ relaxation mechanism can be explained for the generation of the nonlinear PA signal. The experiment can be performed using a continuous wave CO₂ laser, a lock-in amplifier and detectors for the laser power and the acoustic signal, which are available in the senior laboratory. This will provide a useful example of phase-sensitive signal detection.

2. Theory

2.1. Brief review of kinetic cooling

If the laser frequency is tuned to a rotational-vibrational transition within a molecular gas sample, part of the laser beam is absorbed. It is preferable for the excited molecules to release their energy via nonradiative decay. Within the infrared wavelength region, the radiative lifetime for excited molecules is long—much longer than nonradiative decay via collisions at atmospheric pressures. During collisions with other molecules, the excited molecules transfer their excitation energy to the translational energy of the collision partners, resulting in an increase in the temperature. Within a closed volume, the latter is accompanied by an increase in pressure. When modulating the absorption by laser radiation, using frequency modulation or amplitude modulation, the pressure inside the gas absorption cell thus varies periodically and can be detected by a microphone. In general, the microphone signal is linearly proportional to the laser power, the gas concentration (at low concentrations) and the absorption coefficient. Each molecule in the sample will contribute to the generation of the total photoacoustic signal [8].

When a CO₂ laser-based photoacoustic system is used to analyse a mixture of ethylene (C₂H₄), H₂O and CO₂ in N₂, there can be a nonlinear relation between the PA signal (amplitude and phase) with the CO₂ concentration [11]. At CO₂ laser radiation wavelengths, all three gases (C₂H₄, H₂O and CO₂) absorb radiation. The de-excitation of the excited levels of C₂H₄ and H₂O is fast and happens via internal relaxation and collisions with other molecules. For excited ro-vibrational levels in CO₂, due to the near resonance with the vibrational level of N₂ and the high quantity of N₂ present in normal air, there is a vibrational energy exchange between CO₂ and N₂. N₂ will be excited at its first vibrational level and CO₂ will be de-excited to the ground state. The first vibrational level of N₂ is known to have a long de-excitation lifetime and will be de-excited only on a millisecond timescale (at atmospheric pressure). The internal redistribution within CO₂ molecules is fast (via collisions) compared to the rate within the N₂. The net result leads to an initial cooling of the gas sample and is therefore known as the kinetic cooling effect [11]. The amplitude and the phase of the PA signal that are then found not only depend on the absorption coefficient and concentration of C₂H₄, H₂O and CO₂, but also on the amount of excitation in the N₂ molecules.

Figure 1. The phasor representation of two photoacoustic signals. The in-phase signal (R_1) is generated by H_2O and C_2H_4 , while the PA signal originating from the CO_2 (R_2) has phase ϕ . The superposition gives (R_T) with phase θ .

2.2. Phasor representation

Here we propose a simple mechanism to show the effect of kinetic cooling. For a single molecule that has fast relaxation, the PA signal is in phase with the laser modulation. If the frequency of laser modulation is ω , this in-phase PA signal is given by

$$S = R \exp(i \omega t) \quad (1)$$

in which S is the normalized photoacoustic signal, i.e. the ratio of the microphone signal and the laser power, and R is the product of the cell constant (the acoustic cell efficiency of bringing acoustic waves to the microphone), the wavelength-dependent absorption coefficient and the concentration of the absorbing molecular species.

In a mixture of H_2O , C_2H_4 , CO_2 and N_2 , the first three gases are excited simultaneously via the absorption of radiation. During de-excitation, the relaxation of H_2O and C_2H_4 molecules is fast, resulting in a PA signal (S_1) that is in phase with the laser modulation:

$$S_1 = R_1 \exp(i \omega t). \quad (2)$$

Next to this, the internal relaxation of the excited CO_2 levels also generates an in-phase PA signal. However, part of the excited energy within CO_2 is transferred via collisions to excite the N_2 . The relaxation of the vibrational excited level in the N_2 is long and causes a kinetic cooling effect. Due to its slow relaxation, the generated PA signal is delayed and shifts in phase relative to the laser modulation. Therefore, the total PA signal originating from the excitation of CO_2 has a phase difference ϕ :

$$S_2 = R_2 \exp(i(\omega t + \phi)). \quad (3)$$

Its phase shift now depends on the concentrations of H_2O and CO_2 molecules and can vary by up to 180° [10]. The superposition of the signals resulting from the in-phase (equation (2)) and out-of-phase (equation (3)) signals results in a total signal S_T with an amplitude R_T and a phase θ given by equation (4):

$$S_T = R_T \exp(i(\omega t + \theta)). \quad (4)$$

Its phasor representation is depicted in figure 1 [12–14]. The PA signal S_1 is in phase with the laser modulation; the phasor is represented by its amplitude R_1 along the horizontal axis. The phasor for the second PA signal S_2 , is represented by its amplitude R_2 and its phase ϕ . The PA signal S_2 lags behind the laser modulation and therefore its phase is negative. These phasors are added vectorially to find the phasor of the total PA signal S_T that is represented by its

Figure 2. The experimental intracavity photoacoustic set-up. The laser cavity is between the mirror and the grating, in which the laser discharge tube is placed for the gain, the PA cell and the chopper to modulate the laser intensity. The gas mixture entering the PA cell originates from compressed gas bottles and flow controllers (FC) to make mixtures of various concentrations. The CO₂ and water vapour concentration are independently measured with sensors.

amplitude R_T and its phase θ . Figure 1 shows that θ is also negative. The horizontal and vertical components of this total PA signal are $R_T \cos\theta$ and $R_T \sin\theta$.

When the amplitudes from the first photoacoustic signals are kept constant (R_1 is constant), which means that the concentrations of H₂O and C₂H₄ are unchanged, the total PA signal (amplitude R_T and phase θ) can depend on the amplitude resulting from the CO₂ concentration. An increase in the CO₂ concentration causes a longer R_2 vector. This is followed by an increase (regardless of the negative sign) in θ . To begin with, R_T will decrease, and then at a certain condition it will increase. A minimum of R_T occurs when R_T and R_2 are perpendicular. In this case its phase (θ_m) follows

$$\theta_m = \phi - 90^\circ. \quad (5)$$

For a constant R_1 the contribution of the second PA signal originating from CO₂ excitation (amplitude R_2 and phase ϕ) can be extracted by measuring the amplitude of the total PA signal R_T and its phase θ . The phase ϕ can be determined from the components of the total signal, $R_T \cos\theta$ and $R_T \sin\theta$, respectively. This will be discussed in section 4.

3. Experiment

The experimental set-up is depicted in figure 2. The continuous wave CO₂ laser consists of a grating (for line tunability over the CO₂ laser lines), a gas discharge tube for the gain and an outcoupling mirror. The laser power is measured with a power meter. To generate the

Table 1. Four experiments were performed (a, b, c, d) at two different CO₂ laser lines. In each experiment, the CO₂ concentration was varied between 350–5000 ppmv.

CO ₂ laser line	
10 P 20	10 P 14
a. H ₂ O : (10.0 ± 0.5) %	b. H ₂ O : (9.8 ± 0.3) %
c. H ₂ O : (9.8 ± 0.5) %	d. H ₂ O : (11.9 ± 0.3) %
C ₂ H ₄ : 1 ppmv	C ₂ H ₄ : 1 ppmv

photoacoustic signal via the amplitude modulation of the laser power a chopper is used. The modulation frequency of the chopper is 1749 Hz, i.e. the resonance frequency of the photoacoustic cell (PA cell). Here the PA cell is placed inside the laser cavity to enhance the sensitivity for gas detection, due to the high intracavity laser power [15]. The intracavity laser power depends on the CO₂ laser line, i.e. around 20 W. An electret microphone detects the pressure changes in the photoacoustic cell. The sensitivity of this microphone is 10 mV Pa⁻¹. To enhance the photoacoustic signal and to reject all other acoustic sound from the environment, a lock-in amplifier (7220 DSP Lock-in Amplifier, EG&G Instruments) is used. The modulation signal from the chopper is used as a reference for the lock-in amplifier. It only amplifies (phase sensitive) at the modulation frequency within a bandwidth of 1 Hz and rejects all other acoustic and electronic noise. A personal computer (PC) provides data acquisition and controls the experiment.

The gas mixture containing N₂, CO₂ and C₂H₄ is fed to the PA cell through flow controllers (FC) to generate mixtures with various CO₂ concentrations. The mixture also contains traces of H₂O. To measure the CO₂ concentration independently, a CO₂ sensor (CO₂-BTA, Vernier) is placed at the outlet of the PA cell. A relative humidity (RH) sensor (RH-BTA, Vernier) is used to monitor the water vapour concentration. The room temperature is also monitored continuously. These sensors, i.e. the CO₂ sensor, the RH sensor and the temperature probe (STS-BTA, Vernier), are connected to a Vernier interface [16]. The data is collected using Vernier Logger Pro software.

Various gas mixing experiments were performed to investigate the effect of CO₂ concentration on the PA signal. Various gas mixing concentrations of N₂, CO₂ and C₂H₄ were achieved by adjusting the flow controllers. The main gas constituent was N₂, while CO₂ and C₂H₄ were at trace gas levels. The photoacoustic effect with a varying amplitude and phase was studied by performing measurements on two different CO₂ laser lines (wavenumbers), i.e. 10P20 (944.1940 cm⁻¹) and 10P14 (949.4793 cm⁻¹) CO₂ laser lines. At these laser lines, the absorption coefficients of C₂H₄ are 1.84 atm⁻¹ cm⁻¹ and 30.4 atm⁻¹ cm⁻¹, respectively [17]. Different combinations of gas mixtures and laser lines used in the experiment are presented in table 1. In this table, the water vapour concentration was calculated from the relative humidity sensor, the temperature during the experiment and the available partial pressure data [18]. In each condition (a, b, c, d) the CO₂ concentration was varied in a range of 350–5000 ppm. In the C₂H₄-containing mixture, the C₂H₄ concentration was kept constant (1 ppmv).

Due to the fast relaxation, the PA signal originating from H₂O and C₂H₄ is only in phase with the laser modulation. At the start of the experiment, the phase of this PA signal was set to zero, indicating it to be the in-phase signal. The PA signal and its phase, as well as the laser

Figure 3. The amplitude (R_T) and the phase (θ) of the PA signal as a function of the CO_2 concentration. The measurements were carried out at the 10P20 laser line. (a) Left panels: amplitude and phase of the PA signal from gas mixtures consisting of N_2 , H_2O and CO_2 . (b) Right panels: N_2 , H_2O , CO_2 and C_2H_4 mixtures.

power, were recorded using a PC. The unit of normalized PA signal was an arbitrary unit (a.u.). The results are presented in figures 3 and 4.

Figure 3 shows the amplitude of the normalized PA signal and its phase measured at the 10P20 laser line. The PA signal comes from traces of water vapour in the N_2 and from CO_2 (figure 3(a)). By increasing the CO_2 concentration, the PA signal amplitude first decreases and then subsequently increases following the CO_2 concentration. At the minimum, a fast change in the phase is observed up to -160° . The minimum amplitude is found at a concentration of 1200 ppmv CO_2 . Similar behaviour is demonstrated in figure 3(b) upon adding to the C_2H_4 gas mixture.

The amplitude and phase of the normalized PA signal at the 10P14 laser line are depicted in figure 4. For a mixture of N_2 , H_2O and CO_2 (figure 4(a), left panel) the behaviour is similar to the measurements at the 10P20 laser line. There is a minimum of amplitude and the phase changes up to -160° . In figure 4(b), by adding C_2H_4 , the photoacoustic amplitude gains about a factor of two. Due to the increase in CO_2 concentration a decrease in the PA signal is observed, but no minimum PA signal is reached. The observed phase change is relatively small, with a maximum phase change of only -10° .

4. Discussion

Using a CO_2 laser-based photoacoustic detection system, it was found that in a mixture with N_2 and CO_2 , the PA signal changes nonlinearly. This phenomenon can be explained using a phasor diagram, as illustrated in figure 1. The effect of changing CO_2 concentrations is demonstrated by the change of θ . Figure 1 shows that θ depends on the proportionality

Figure 4. The amplitude (R_T) and the phase (θ) of the PA signal as a function of the CO_2 concentration. The measurements were carried out on the 10P14 laser line. (a) Left panels: amplitude and phase of the PA signal from the gas mixtures consisting of N_2 , H_2O and CO_2 . (b) Right panels: N_2 , H_2O , CO_2 and C_2H_4 mixtures. Notice the scales on the panels are not the same.

between the in-phase signal (R_1) and the signal originating from the relaxation of CO_2 (R_2). This observation is more prominent if the in-phase signal is relatively small. On the other hand, for a large in-phase signal the change in θ is small.

Phase changes up to -160° are observed at the 10P20 laser line in which the total in-phase signal is small. For this measurement, the in-phase signal is generated by water vapour (figure 3(a)) and by water vapour and C_2H_4 (figure 3(b)). The absorption coefficient of C_2H_4 in this 10P20 laser line is small. Therefore, the added C_2H_4 does not increase the in-phase signal significantly. The measurements at the 10P14 laser line show different behaviour. For a mixture of N_2 , H_2O and CO_2 the phase also changes up to -160° (see figure 4(a)). This is caused by a small, in-phase signal from the water vapour. Adding C_2H_4 (figure 4(b)) using the 10P14 laser lines gives only a small phase change in θ around -10° . This small phase change is due to the dominant in-phase signal generated by C_2H_4 . At this CO_2 laser line C_2H_4 has a strong absorption coefficient.

In the first experiment, figure 3(a), a minimum R_T is observed for a θ between 62° and 88° . For the same concentration of water vapour (and C_2H_4), R_1 is constant. An increase in the CO_2 concentration leads to an increase in the amplitude R_2 and causes an increase in θ . It is clear that if θ increases then R_T first decreases. When the phasor R_T and R_2 are perpendicular, R_T becomes a minimum. A similar situation can be observed in figures 3(b) and 4(a). In figure 4(b), the in-phase PA signal is from H_2O and C_2H_4 . Due to its strong absorption, this in-phase PA signal is much higher than the out-of-phase PA signal, and as such the change in θ is small. An increase in the CO_2 concentration leads to a decrease in R_T , with no minimum value, since that value cannot be reached.

Figure 5. The relation of the components of the total PA signal, i.e. $R_T \sin\theta$ and $R_T \cos\theta$, for various CO_2 concentrations. The measurement was carried out on the 10P20 laser line. The gas mixture consists of N_2 , H_2O and CO_2 . The dashed line is an indication of the vertical axis that goes through the origin (0, 0) in figure 1. The solid line is a linear fit to obtain the phase ϕ .

Table 2. The phase (ϕ) of phasor R_2 , the calculated and observed phase (θ_m) of the phasor R_T .

Source	ϕ	θ_m	
		Calculated	Observed
Figure 3(a)	$(-166 \pm 2)^\circ$	$(-76 \pm 2)^\circ$	$(-71 \pm 8)^\circ$
Figure 3(b)	$(-168 \pm 2)^\circ$	$(-78 \pm 2)^\circ$	$(-70 \pm 5)^\circ$
Figure 4(a)	$(-169 \pm 2)^\circ$	$(-79 \pm 2)^\circ$	$(-72 \pm 5)^\circ$

To identify the contribution of CO_2 on the total PA signal for each CO_2 concentration, we decompose the total signal (see figure 1) into two parts, i.e. $R_T \cos\theta$ and $R_T \sin\theta$. These two parts can be obtained from the R_T and θ of each point presented in figures 3 and 4. In accordance with figure 1, the coordinate of the tip of the phasor of the total PA signal is $R_T \cos\theta$, $R_T \sin\theta$. Using the data presented in figure 3(a), these coordinates are depicted as points for various CO_2 concentrations in figure 5.

The amplitudes of the total PA signal (R_T) can be traced from the origin to these points. A straight line through these points shows the direction of the phasor R_2 for different CO_2 concentrations. This phasor represents the PA signal originating from the relaxation of the CO_2 in the mixture of N_2 , H_2O and CO_2 . It also shows the constant ϕ from equation (3) and figure 1. From the linear fit in figure 5, ϕ can be obtained, i.e. $(-166^\circ \pm 1^\circ)$. For different conditions (mixtures and laser lines), the obtained ϕ is presented in table 2.

The minimum of R_T will be found when the phasors R_T and R_2 are perpendicular. In this condition, the phase (θ_m) of phasor R_T can be calculated using equation (5). This θ_m can also be observed directly in figures 3(a), (b) and 4(a). The observed θ_m can be determined from the interpolation on these figures. The calculated and observed θ_m are presented in table 2. It can be seen that the calculated θ_m is the same as the observed θ_m .

The energy absorbed by the CO_2 molecules is used to generate the PA signal directly, and also to vibrationally excite the N_2 . Subsequently, the relaxation of the excited N_2 also

Figure 6. The phasor representation of two photoacoustic signals originating from the excitation of CO_2 only. The first in-phase signal (R_A) is generated by the direct relaxation of excited CO_2 . The second signal (R_B, δ) is generated by the relaxation of excited N_2 . The total PA signal originating from the CO_2 excitation is therefore represented by the amplitude R_2 and phase ϕ .

generates a PA signal, but on a longer timescale. The direct PA signal from the CO_2 (R_A) is in phase with the laser modulation (figure 6). The out-of-phase PA signal is caused by the slow relaxation of N_2 (R_B) with the phase (δ). Therefore, the total PA signal (R_2) originating from the CO_2 excitation shows a phase (ϕ) to the laser modulation. This situation is similar to figure 1, however it is now only for CO_2 . The amplitudes of both signals (R_A and R_B) depend on the CO_2 concentration, and are proportional to each other. The relaxation time of excited N_2 depends on the relaxation times for the vibrational-translational energy exchange between molecules in the gas sample [10, 11]. Therefore for the same conditions δ is expected to be constant. As a result, the amplitude R_2 is affected by the CO_2 concentration, while ϕ is independent of it.

The phase (ϕ) was found to have a value of more than 90° , with R_B longer than R_A . This indicates that the relaxation of the excited CO_2 is more efficient in transferring energy to N_2 .

The proposed simple model is adequate for explaining the effect of kinetic cooling. This is based on the approximation that δ , due to the relaxation of excited N_2 , is constant and independent of the CO_2 concentration. A closer inspection of figure 5 shows a small deviation from the straight line. This nonlinear situation reveals the CO_2 dependence on the phase δ . The source of this phase change is the relaxation time of the excited N_2 , which also depends on the CO_2 concentration [9–11].

5. Conclusion

The presence of vibrationally excited CO_2 in a gas sample exhibits a special condition for the generation of the PA signal. During de-excitation, CO_2 transfers its energy to vibrationally excite N_2 , causing a kinetic cooling effect. This mechanism leads to the nonlinear dependence of the PA signal amplitude on the CO_2 concentration, as well as the phase changes. The effect of kinetic cooling on the amplitude and phase of the PA signal is prominent, if the photoacoustic signal originating from CO_2 excitation is comparable with the signal from other molecules in the gas sample.

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References

- [1] Rush W F and Heubler J E 1982 Photoacoustic effect demonstration *Am. J. Phys.* **50** 669
- [2] Euler M, Niemann K and Müller A 2000 Hearing light *Phys. Teach.* **38** 356–8
- [3] Euler M 2001 Hands-on resonance-enhanced photoacoustic detection *Phys. Teach.* **39** 406–9
- [4] Zhu Z, Du L, Zhang Y, Wang S, Zhou H and Gao W 2015 Hearing light from an incandescent bulb *Eur. J. Phys.* **36** 1–9
- [5] Nikitichev D I, Xia W, Hill E, Mosse C A, Perkins T, Konyn K, Ourselin S, Desjardins A E and Vercauteren T 2016 Music-of-light stethoscope: a demonstration of the photoacoustic effect *Phys. Educ.* **51** 1–9
- [6] Harren F J M, Mandon J and Cristescu S M 2012 Photoacoustic spectroscopy in trace gas monitoring *Encyclopedia of Analytical Chemistry* ed R A Meyers (Chichester: J. Wiley) pp 1–24
- [7] Fukuhara A, Kaneko F and Ogawa N 2012 Simple model of a photoacoustic system as a CR circuit *Eur. J. Phys.* **33** 623–35
- [8] Zharov V P and Letokhov V S 1986 *Laser Photoacoustic Spectroscopy* (Berlin: Springer Verlag)
- [9] Hammerich M, Olafsson A and Henningsen J 1992 Photoacoustic study of kinetic cooling *Chem. Phys.* **163** 173–8
- [10] Rooth R A, Verhage A J L and Wouters L W 1990 Photoacoustic measurement of ammonia in the atmosphere: influence of water vapour and carbon dioxide *Appl. Opt.* **29** 3643–52
- [11] Moeckli M A, Hilbes C and Sigrist M W 1998 Photoacoustic multicomponent gas analysis using a Levenberg–Marquardt fitting algorithm *Appl. Phys. B* **67** 449–58
- [12] Serway R A and Vuille C 2012 *College Physics* 9th edn (Boston MA: Brooks/Cole) p 730
- [13] Young H D 2012 *Sears & Zemansky's College Physics* 9th edn (San Francisco CA: Addison-Wesley) pp 735–6
- [14] Rossing T D and Fletcher N H 1995 *Principles of Vibration and Sound* (New York: Springer Verlag) p 7
- [15] Harren F J M, Bijnen F G C, Reusss J, Voeselek L A C J and Blom C W P M 1990 Sensitive intracavity photoacoustic measurements with a CO₂ waveguide laser *Appl. Phys. B* **50** 137–44
- [16] Vernier Software & Technology, 13979 SW Millikan Way, Beaverton, OR 97005-2886 <http://vernier.com/>
- [17] Brewer R J, Bruce C W and Mater J L 1982 Photoacoustic spectroscopy of C₂H₄ at the 9- and 10 μ m C¹²O₂¹⁶ laser wavelengths *Appl. Opt.* **21** 4092–100
- [18] Lide D R 1995 *CRC Handbook of Chemistry and Physics* 76th edn (Boca Raton: CRC Press) pp 6–15