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# CARS SPECTROSCOPY OF GUN PROPELLANT FLAMES— HIGHER HOT BAND AND CONCENTRATION EFFECTS



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Nitrogen Coherent Anti-Stokes Raman Scattering (CARS) spectra from nitrate-ester propellant flames contain several features not reported in nitrogen CARS spectra from other flames. Prominent among these features is a high intensity peak (30% maximum) 30 cm(-1)to the low energy side of the first hot band. Nitrogen CARS spectra from air/argon mixture containing from 1% to 30% air changed substantially with concentration but agreed with calculated spectra to better than 6%. Nitrogen CARS spectra from propane/air flames of

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various equivalence ratios showed a resolved second hot band, Q(32) at 2,269 cm(-1) and the presence of the third hot band, Q(43), near 2,241 cm(-1). Temperatures determined from Q(32) agreed, within experimental error, with those determined with Q(10) at 2,296 cm(-1). Temperature trends for the various equivalence ratios agreed with thermochemical predictions, allowing the accuracy to be assessed at better than 5%. The good agreement of nonplanar and planar BOXCARS validated the earlier planar BOXCARS measurements. Nitrogen CARS calculations agreed well with experimental propellant spectra at the 10% nitrogen concentration expected from thermochemical calculations. The calculated spectra show the presence of Q(32) near 30% maximum intensity as seen in the propellant spectra.

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## INTRODUCTION

Measurements of temperature and concentration spatial profiles in propellant and related laboratory flames should provide experimental results needed to identify the controlling mechanisms of propellant combustion. These measurements are difficult to make with conventional methods since propellant flames are often transient, incandescent, and particle-laden. Coherent Anti-Stokes Raman Scattering (CARS), due to its high intensity and coherent nature, provides a means of probing propellant flames. The CARS signal can be generated from a spatially, well defined region in the flame on the order of 1 $mm^3$ within the time duration of the laser pulse. CARS involves the interaction of two high intensity laser beams, the pump and Stokes beams, at angular frequencies $\omega_\ell$ and $\omega_s$, respectively. When $\omega_\ell$ and $\omega_s$ are separated by a Raman resonance frequency, CARS, $\omega_{as}$ is generated at the anti-Stokes frequency. CARS signal strength is proportional to the square of the modulus of the third-order electric susceptibility, $/\chi^{(3)}/$. The susceptibility is the sum of a resonant, $\chi_r$, and nonresonant term, $\chi_{nr}$. $\chi_r$ can be expanded into a real and imaginary term.

$$/\chi^{(3)}/^2 = /\chi_r' + i\chi_r'' + \chi_{nr}/^2 \tag{1}$$

$\chi_r'$ and $\chi_r''$ have dispersive and resonant line shapes, respectively; therefore, at low concentration the CARS lineshape becomes dispersive.

$$/\chi^{(3)}/^2 = /\chi_r' \chi_{nr} + \chi_{nr}^2/ \tag{2}$$

Nitrogen CARS spectra have been reported for nitrate-ester propellant flames (ref 1 through 3). The propellant spectra contained several features that had not been reported in nitrogen CARS spectra from other flames. The novel features in the propellant nitrogen CARS spectra can be attributed to the lower concentration of nitrogen, the high temperature of the flame, and the lower resolution necessitated by the low intensity of the spectra. Prominent among the novel features was a high intensity (30% maximum) peak 30 $cm^{-1}$ to the low energy side of the first hot band. This peak had not been reported in previous investigations on flames. To determine the nature of the novel spectral features, the following investigations were undertaken:

1. Nitrogen CARS spectra from air/argon mixtures with nitrogen at concentrations near that in the propellant flame (10%).

2. Nitrogen CARS spectra from propane/air flames of various equivalence ratios with emphasis on the behavior of the second hot band. Thermochemical calculations were performed to assess the accuracy of the experimentally determined temperatures.

## EXPERIMENTAL

CARS spectra were generated using apparatus with both planar and nonplanar BOXCARS (ref 4) phasematching (fig. 1), using the apparatus shown in figure 2. The pump laser beam, $\omega_\ell$ is produced by a Quanta-Ray DCR-1A Nd/YAG laser. The output of the Nd/YAG laser at 1.06 microns (700 mj) is doubled to generate the pump beam, $\omega_\ell$, at 5,320 Å (250 mj) with a bandwidth of about 1 $cm^{-1}$. The pump beam is separated from the primary beam using prisms. Forty percent of the pump beam is split off ($BS_1$) to pump a dye laser to generate the Stokes beam, $\omega_s$. The dye laser is operated broadband to produce 30 mj centered at 6,070 Å with a bandwidth of about 150 $cm^{-1}$. To achieve BOXCARS geometry, the pump is split using a 50% beamsplitter, $BS_2$. In planar BOXCARS, the $\omega_\ell$ beam is reflected from a dichroic (DC) which transmits the stokes beam, and $\omega_\ell'$ is separately reflected along another path so that the pump beams are separated at the focusing lens. The planar BOXCARS signal, $\omega_{as}$, which is generated along $\omega_\ell$, is isolated by prism and spatial filtering. In nonplanar BOXCARS, $\omega_s$ is introduced below the plane of $\omega_\ell$ at the focusing lens to produce a spatially isolated $\omega_{as}$ which is focused onto the slits of a monochromator fitted with a PAR SIT detector. The signal from the detector is sent to an OMA2 for processing.

In these experiments a 200-mm focusing lens was used with a pump beam crossing angle of 5° in planar BOXCARS. In nonplanar BOXCARS, the $\omega_\ell$, $\omega_\ell'$, and $\omega_s$ beams are situated on a circle of 1-inch radius at the focusing lens with $\omega_\ell$ and $\omega_\ell'$ in the horizontal plane and $\omega_s$ in the vertical plane. A 1/4-meter monochromator equipped with a 1,800 line/mm grating and 100-micron slits was used for dispersal of $\omega_{as}$. Neon spectral lines were used to determine the resolution and wavelength calibration of the monochrometer.

## RESULTS

Temperature is determined by comparison of the experimental $N_2$ spectra with spectra calculated according to the procedure given by Hall (ref 5) using parameters given in references 5 through 7. The spectral parameters of $\omega_s$ were determined by flowing argon with some admixture of air through the burner to generate nonresonant CARS spectra which mirrors the spectral shape of $\omega_s$. This spectra, in addition to providing the spectral parameters of $\omega_s$ illustrates the dependence of CARS spectra on concentration. CARS spectra from room temperature air/argon mixtures containing from 1% to 100% air are shown in figures 3 and 4. A comparison of calculated and experimental spectra in a 9% and 20% air/argon mixture is shown in figures 5 and 6, respectively. The ratio of the maximum intensities at $Q_{10}$ and the nonresonant susceptibility is a direct measure of the concentration. Experimental and calculated maximum $Q_{10}$ to nonresonant susceptibility ratio are given in table 1 and shown in figure 7. The agreement between theory and experimental is given in table 1 as 6.1%. The depth of the dip goes to increasingly larger intensity as the concentration decreases. A similar effect of concentration on CARS CO spectra was observed by Eckbreth (ref 4). The spectrum shown in figure 8 was determined using nonplanar BOXCARS with a slit width of 6.4 $cm^{-1}$ and 2.38 $cm^{-1}$ per channel as determined from the room temperature $N_2$ CARS spectrum shown in figures 5, 6, and 7. The spectral parameters determined for $\omega_s$ from

spectra similar to that in figure 5 were $\omega_s^{max}$ at 16,500 $cm^{-1}$ with full width at half height (FWHH) of 130 $cm^{-1}$. These experimental parameters pertain to all the other reported nonplanar BOXCARS spectra. The experimentally determined parameters were used to generate CARS spectra with temperatures varying from 1,500 to 3,000 K (at 250-K intervals) which are shown in figure 9. The $Q_{10}$, $Q_{21}$, and $Q_{32}$ peaks are seen to be clearly resolved at near to 2,325, 2,296, and 2,269 $cm^{-1}$, respectively. The bands shift slightly to the red as the temperature is raised. A shoulder near 2,241 $cm^{-1}$, attributable to $Q_{43}$, is seen to be almost resolved at 3,000 K. The average calculated separation between peaks is 28 $cm^{-1}$. The relative height of the $Q_{10}$ peak determined experimentally was previously used to determine temperature from the calculated spectra (ref 4). Calculations made at small intervals (20 K) such as shown in figure 10 are, in practice, used to determine temperature.

Measurements of $N_2$ CARS spectra were made immediately above the reaction zone on the centerline of the burner with both nonplanar and planar BOXCARS. The nonplanar results were obtained at fuel/air equivalence ratios of 1.02, 0.81, and 1.27. The 1.02 and 0.81 equivalence ratio results are shown in figures 11 and 12, respectively, along with the calculated spectra. (The 1.27 equivalence ratio results look very similar to the 0.81 results.) The planar results are given in figure 13.

The $Q_{32}$ peak is resolved and occurs at the calculated frequency. The $Q_{43}$ is not clearly resolved but can be identified as occurring at the calculated position.

The results of the thermochemical calculations performed with the NASA-LEWIS computer code at the experimental equivalence ratios are given in table 2. The temperatures determined from the $Q_{21}$ and $Q_{32}$ peaks, $T_{21}$ and $T_{32}$, respectively, are given in table 3. The temperatures determined from two different spectra for the equivalence ratio 1.02 showed that the precision of the method was quite good. The agreement between $T_{21}$ and $T_{32}$ was within the accuracy of the experimental data; however, $T_{32}$ was systematically lower than $T_{21}$. This may result from slight inaccuracies in the $\omega_s$ parameters. Since $T_{21}$ and $T_{32}$ agreed within the accuracy of the data, no attempt was made to vary the $\omega_s$ parameters. A comparison of the experimental and thermochemically calculated temperatures is given in table 4. The experimentally determined temperatures are lower than the calculated adiabatic flame temperatures by about 10% on average. This is attributable to heat loss by radiation, thermal conduction, or diffusion which vary with burner design. The magnitude of the error is consistent with previous studies (ref 8). The error determined from the normalized temperatures (assuming constant percentage heat loss) is consistent with the known errors in CARS temperature determination and the flowmeters. The error is predominately in the flowmeters since the precision of CARS was shown above to be better.

Temperatures were also determined at the equivalence ratio of 1.02 with the planar BOXCARS configuration. The $\omega_s$ parameters were $\omega_s^{max}$ at 16,497 $cm^{-1}$ with a width of 153 $cm^{-1}$. The slit width determined from the room temperature spectra was 9.6 $cm^{-1}$ with 2.336 $cm^{-1}$ per channel. A comparison of the planar and nonplanar $T_{21}$ and $T_{32}$ temperatures is shown in table 5. The agreement is very good considering the substantial changes made in the apparatus.

## DISCUSSION

The high temperature and low concentration (less than 30%) of each product in propellant flames introduce features of $N_2$ CARS not previously reported. In addition, to attain the required intensity, lower resolution than that used in other studies was used.

Concentration as shown in figures 3, 4, 5, and 6 alters the appearance of $N_2$ CARS spectra at room temperature. The effect of concentration at 2,500 K is shown in figure 14. At higher concentration of room temperature spectra, the calculated maximum intensity falls as the square of the concentration. However, at high temperatures the steepness of the decline of the signal with concentration begins to moderate at 50% air as opposed to room temperature where moderation does not begin to occur until 5% air is reached. This difference occurs because the high temperature spectra is spectrally wider than the room temperature spectra. As a consequence, the maximum intensity at high temperature is less relative to the nonresonant susceptibility than at low temperatures. At the 10% level, the signal is decreased from the 100% level by factors of 85 and 25 at 298 and 2,500 K, respectively. This lessening of the square root dependence of intensity on concentration makes possible CARS measurements in flames at lower levels of the concentration of products.

The $Q_{32}$ hot band is much more sensitive to concentration than $Q_{21}$. At the 50% level, $Q_{32}$ has more than doubled in intensity while $Q_{21}$ has only increased by a few percent. Thus, high temperature and low concentration result in high intensity of $Q_{32}$ in the previously reported propellant spectra. The results given in tables 3 through 5 establish the utility of $Q_{32}$ for measurement of temperature. The results in figure 14 indicate that $Q_{32}$ is useful for estimation of the concentration in the range 10% to 100%, given an approximate temperature from $Q_{10}$. Below 10%, if a spectrum can be obtained, the depth of the dip on the high energy side of $Q_{10}$ is useful for estimation of the concentration. These initial estimates of temperature and concentration should be used as input to a least-squares routine to accurately determine temperature and concentration from the spectrum. In the situation where all species are present below the 30% level, it becomes necessary to determine temperature and concentration simultaneously.

The results obtained in comparison of planar and nonplanar BOXCARS indicate that configuration can have an effect on the resolution of the observed spectra. Nonplanar and planar BOXCARS were observed to give spectral resolutions of 6.4 and 9.6 $cm^{-1}$, respectively. This may be due to some distortion of the spectrum resulting from the additional optical elements in planar BOXCARS. It is also possible that the positioning of the CARS signal was not optimized in the planar BOXCARS configuration. The intensity of the CARS signal was higher in the planar configuration which may have some effect on the resolution. Since the spectra and temperatures were the same for planar and nonplanar BOXCARS, no clipping by the slit of the prism-dispersed planar BOXCARS signal is evident. However, the $cm^{-1}$/channel of the planar BOXCARS signal was reduced from the 2.34 to 2.20 to adequately match the spectrum. This was not necessary in nonplanar BOXCARS and may reflect the additional dispersion due to the prism used in planar BOXCARS.

The spectral features observed in propane/air flames and air/ar mixtures can be used to interpret the previously reported propellant spectra which are intermediate between the 25% air (18% $N_2$) and 50% air (35% $N_2$) spectra shown in figure 14. The calculated concentration of $N_2$ in the propellant was 10%. However, the nonresonant susceptibility in the propellant flame is higher than the value used for the propane/air flame; this would reduce the computed concentration. Differences in spectral properties of $\omega_s$ may account for the remaining difference. Alternately there could be some initial mixing in of air. Further work will be needed to resolve this. This spectral resolution of 8 $cm^{-1}$ is consistent with the use of planar BOXCARS to obtain the propellant spectra.

The previously obtained propellant spectrum is in satisfactory agreement with calculations, properly accounting for concentration and using the $Q_{32}$ hot band. Further measurements of M31 and similar propellants are planned. These propellants would have a flame temperature near 2,500 K and $N_2$ concentration near 30%. The $10^2$-$10^3$ counts per shot obtained in the 2,000 K propane/air flame would be reduced by a factor of 2.5 by an increase of temperature to 2,500 K and a factor of 4 by a decrease of $N_2$ concentration to 30% to give an overall order of magnitude reduction in signal which would still be adequate for making measurements. $CH_4/N_2O$ and other similar flames will be studied to aid in interpretation of the propellant flames.

## CONCLUSIONS

Nitrogen CARS spectra from air/ar mixtures with $N_2$ present at concentrations from 1% to 100% air changed substantially with concentration but agreed well with calculated spectra. Nitrogen CARS spectra from propane/air flames of various equivalence ratios showed a resolved second hot band, $Q_{32}$, and the presence of the third hot band, $Q_{43}$. Temperatures determined from $Q_{32}$ were in accord, within experimental error, with those determined from the first hot band, $Q_{21}$. Temperature trends for the various equivalence ratios agreed with the predictions of NASA-LEWIS thermochemical-calculations. The correlation with thermochemical-chemical calculations allowed the accuracy of the experimental measurements to be assessed at better than 5%. Nonplanar BOXCARS gave spectra similar, within experimental error, to that obtained using planar BOXCARS, thus verifying previous work employing planar BOXCARS. Calculations at near the temperature of propellant flames are similar to propellant flame spectra previously obtained at the 10% concentration expected from thermochemical calculations. The calculated spectra show the presence of $Q_{32}$ near 30% maximum intensity as seen in the experimental propellant spectra.

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Table 1. Concentration of air (%) in air/ar mixtures at 300 K

| *$C_{experimental}$ (%) | *$C_{calculated}$ (%) | Difference between columns 1 and 2 | % Difference between columns 1 and 2 |
|---|---|---|---|
| 7.06 | 5.92 | 1.1 | 16.1 |
| 8.54 | 7.80 | 0.7 | 8.7 |
| 12.0 | 11.6 | 0.4 | 3.3 |
| 13.8 | 14.8 | -1.0 | 7.2 |
| 19.7 | 18.8 | 0.9 | 4.5 |
| 22.8 | 22.7 | 0.1 | 0.50 |
| 30.2 | 31.0 | -0.8 | 2.65 |
| Mean ($\sigma$) | | 0.7 (0.3) | 6.1 (5.1) |

* Concentration

Table 2. Thermochemical calculations

| Equivalence ratio | Temperature (K) | $N_2$ (%) | $H_2O$ (%) | $CO_2$ (%) | CO (%) | $H_2$ (%) |
|---|---|---|---|---|---|---|
| 0.81 | 2,085 | 73 | 13 | 10 | 1 | - |
| 1.01 | 2,273 | 71 | 15 | 10 | 2 | - |
| 1.27 | 2,143 | 67 | 15 | 7 | 7 | 3 |

Table 3. Temperature determined from nonplanar BOXCARS

| Equivalence ratio | Temperature (K) | | | | | |
|---|---|---|---|---|---|---|
| | $T_{21}$ | (σ)* | $T_{32}$ | (σ) | $T_{avg}$ | (σ) |
| 0.81 | 1,932 | (29) | 1,843 | (69) | 1,888 | (63) |
| 1.02 | 2,003 | (54) | 1,934 | (116) | 1,969 | (49) |
| 1.02 | 1,990 | (38) | 1,913 | (74) | 1,952 | (54) |
| 1.27 | 1,914 | (29) | 1,853 | (81) | 1,884 | (43) |

Table 4. Comparison of experimental and theoretical temperatures

| Equivalence ratio | Temperature (K) | | | | | |
|---|---|---|---|---|---|---|
| | $T_{calc}$ | $T_{21}$[a] | $\Delta T$ | $T_{calc}$[b] | $T_{21}$[b] | $\%\Delta T$ |
| 1.02 | 2,276 | 1,997 | 279 | 1 | 1 | |
| 1.27 | 2,143 | 1,914 | 229 | 0.94 | 0.96 | 2 |
| 0.81 | 2,085 | 1,932 | 153 | 0.92 | 0.97 | 5 |

[a] $\Delta T = T_{cal} - T_{21}$.

[b] Normalized temperature.

Table 5. Comparison of planar and nonplanar BOXCARS temperatures

| Configuration | Temperature (K) | | | | | |
|---|---|---|---|---|---|---|
| | $T_{21}$ | ($\sigma$) | $T_{32}$ | ($\sigma$) | $T_{avg}$ | ($\sigma$) |
| Planar | 2,021 | (48) | 1,902 | (109) | 1,962 | (84) |
| Nonplanar | 1,990 | (38) | 1,913 | (74) | 1,952 | (54) |

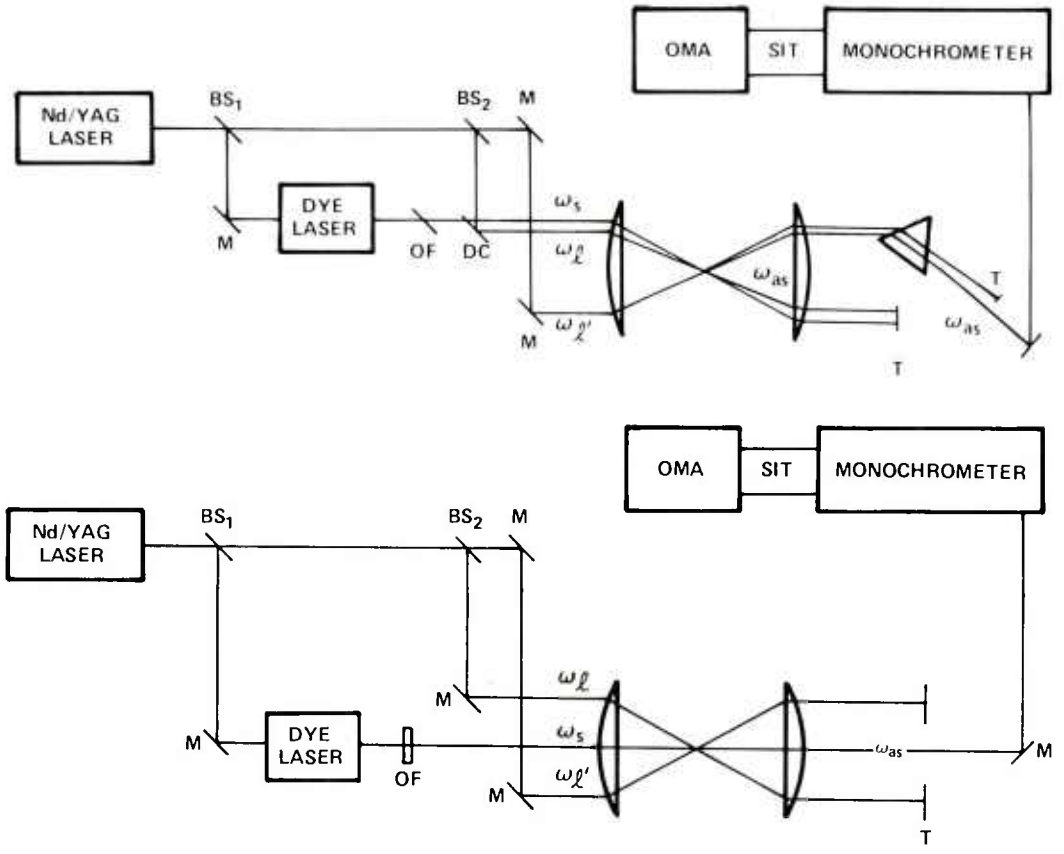


Figure 1. Phase matching

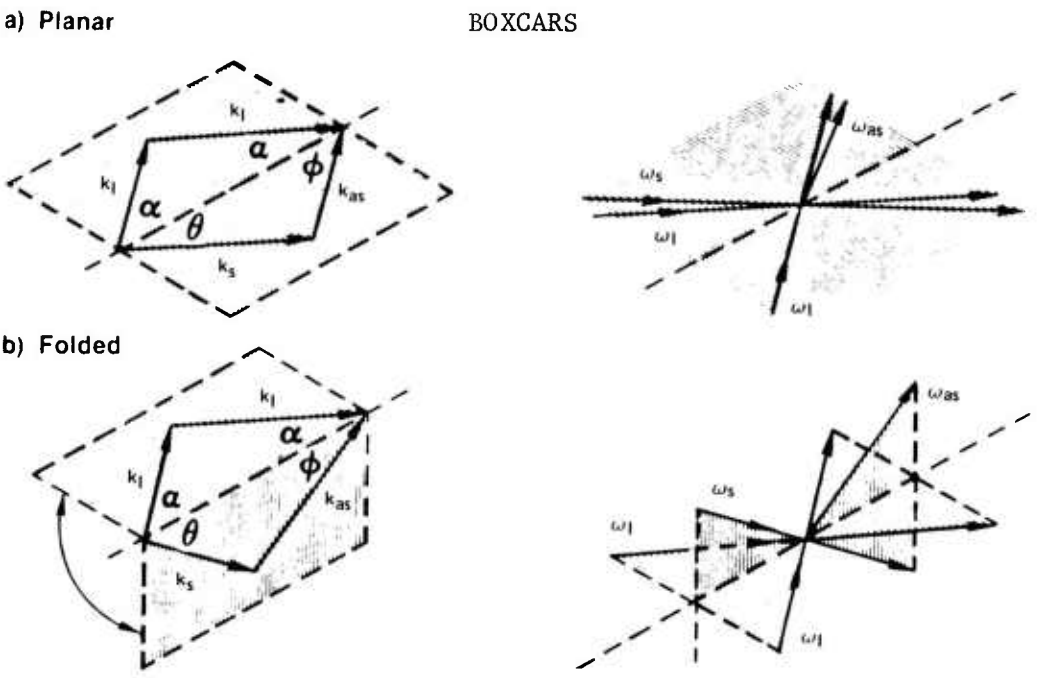


Figure 2. CARS spectrometer

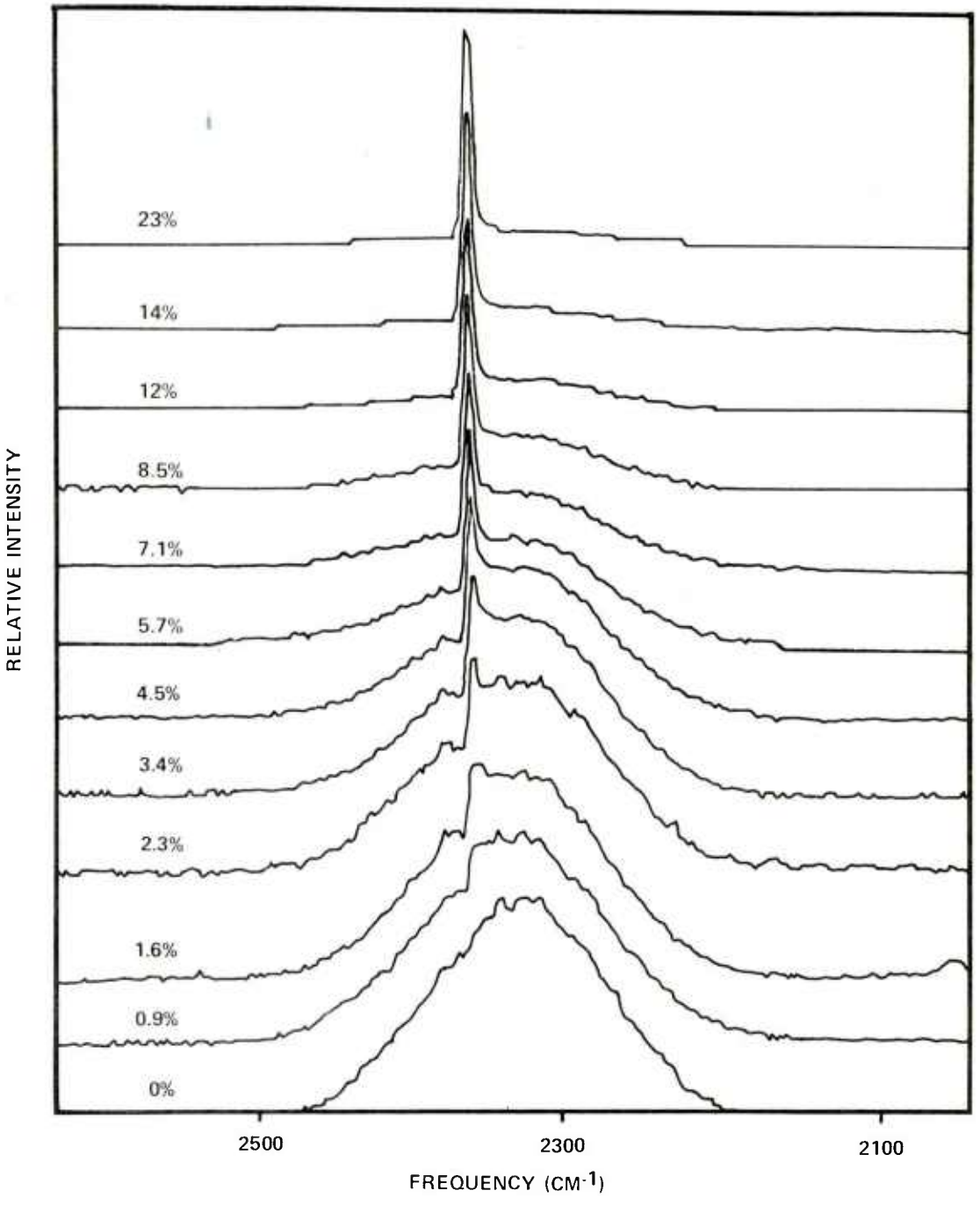


Figure 3. Normalized nitrogen CARS spectra from room temperature air/argon mixture containing 0% to 23% air

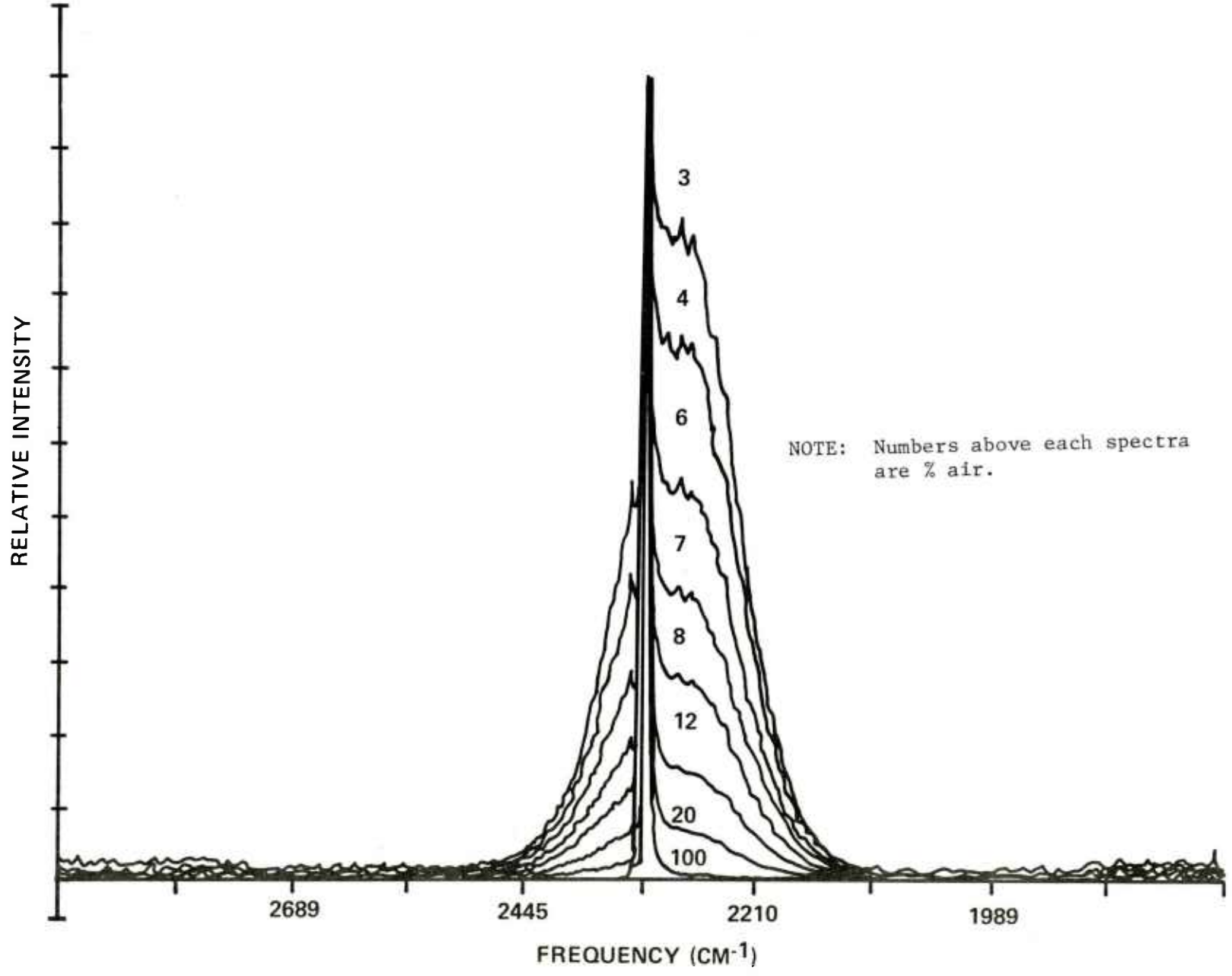


Figure 4. Normalized nitrogen CARS spectra from room temperature air/argon mixtures containing 3% to 100% air

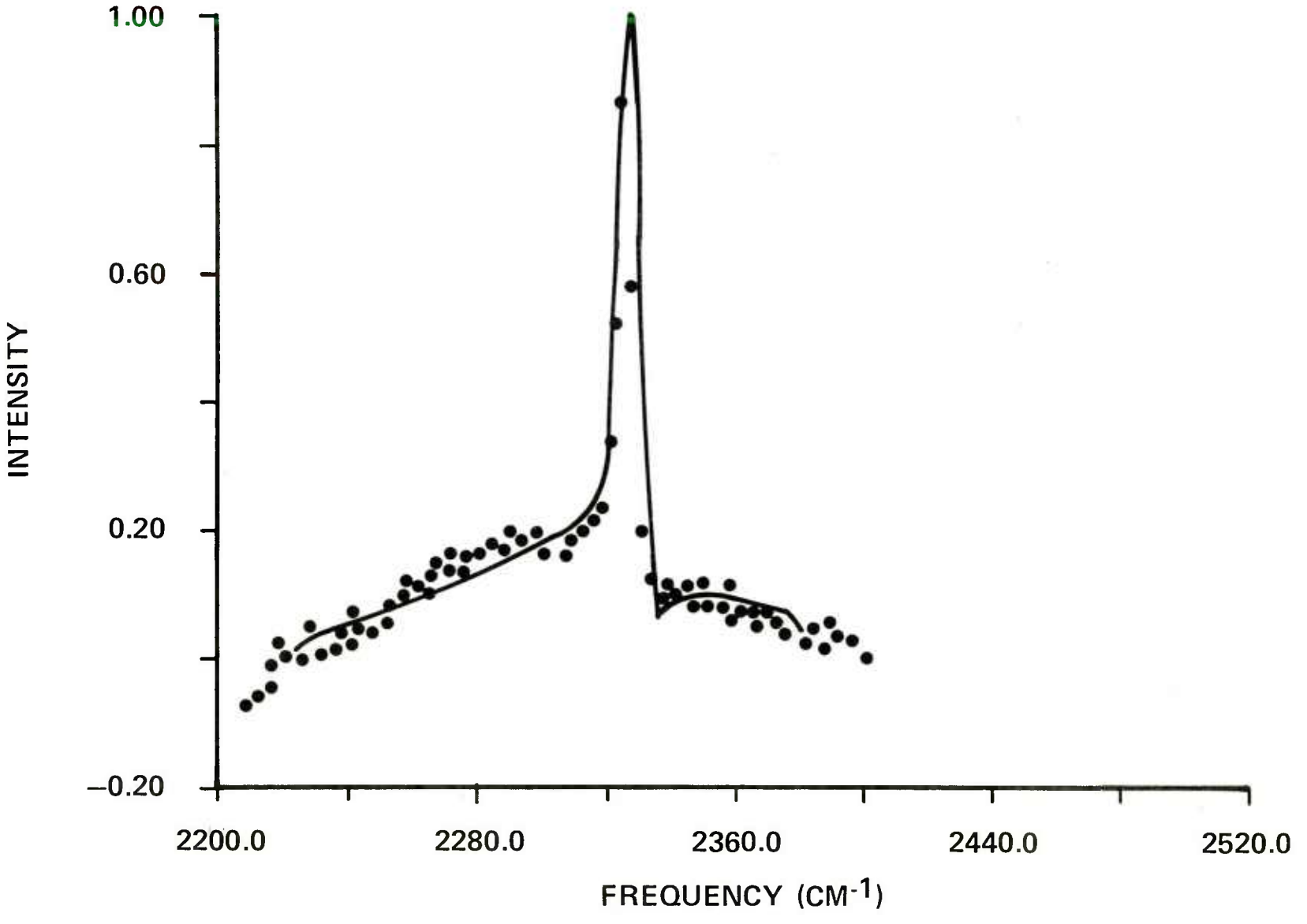


Figure 5. Experimental (.) and calculated $N_2$ CARS spectra at room temperature in a 9% air/argon mixture (nonplanar CARS)

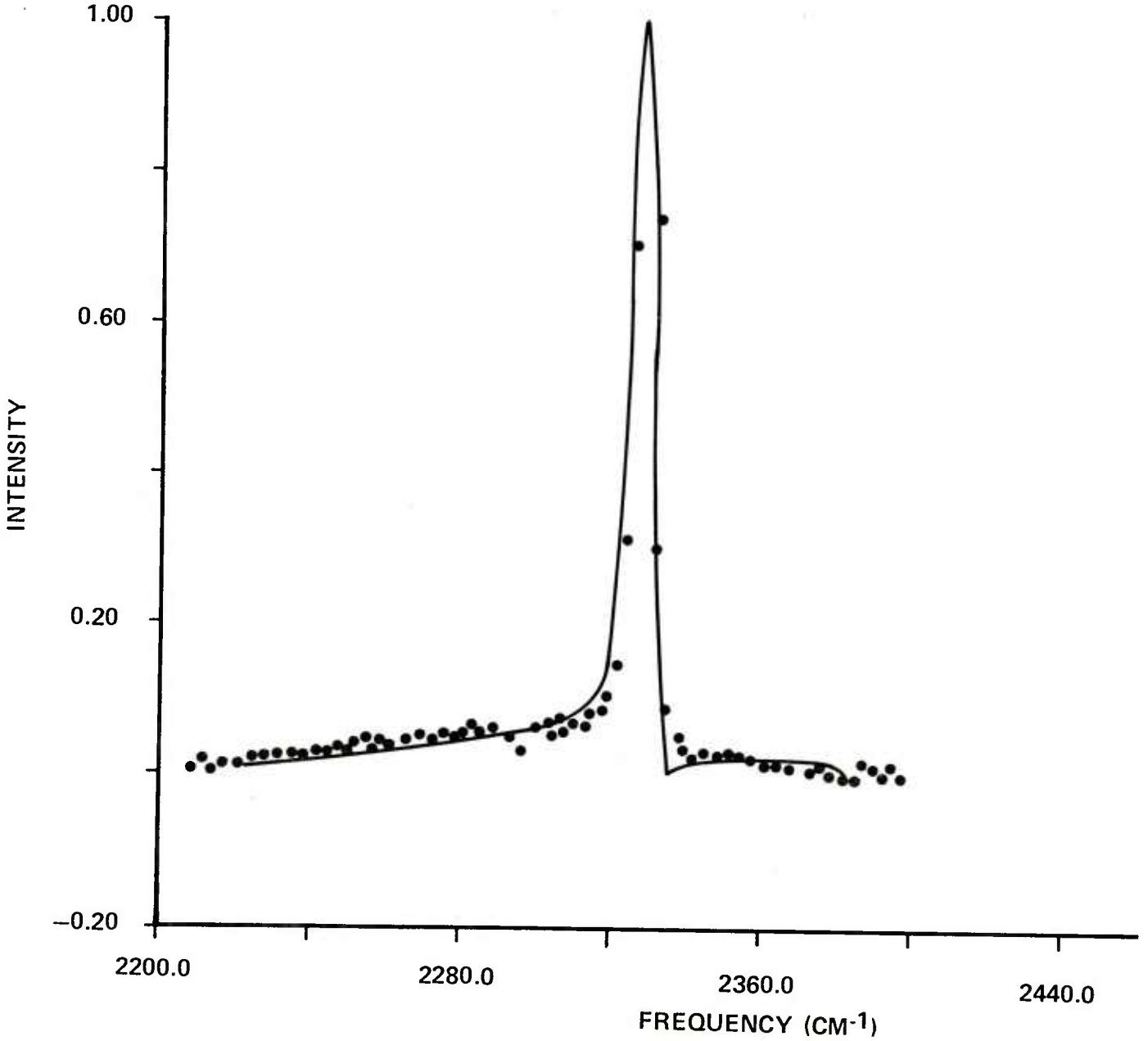


Figure 6. Experimental (.) and calculated $N_2$ CARS spectra at room temperature in a 20% air/argon mixture (nonplanar CARS)

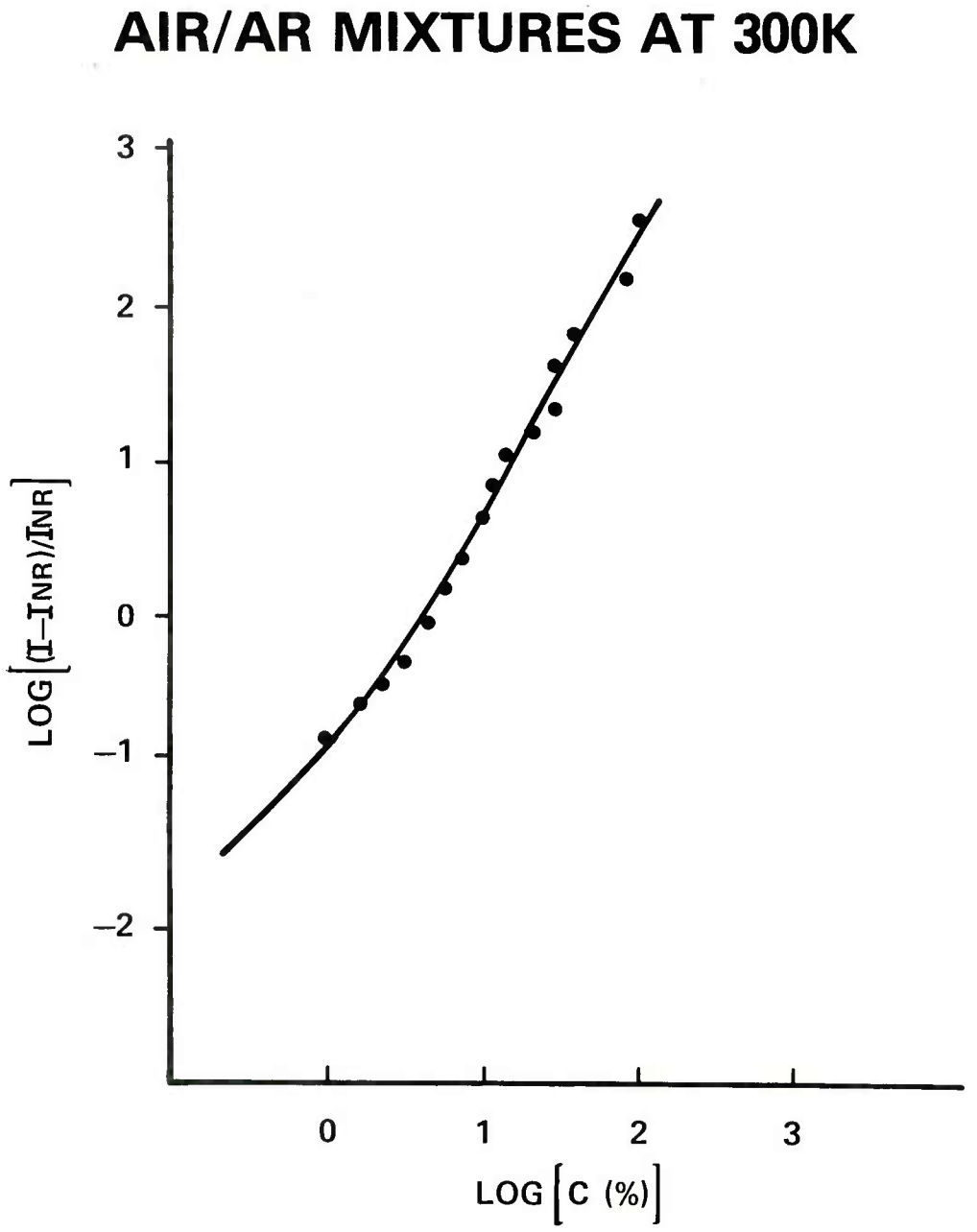


Figure 7. Experimental (.) and theoretical log $[(I_{10} - I_{NR})/I_{NR}]$ where $I_{10}$ and $I_{NR}$ are the maximum intensities of nitrogen $Q_{10}$ and the nonresonant susceptibility versus log [C(%)]

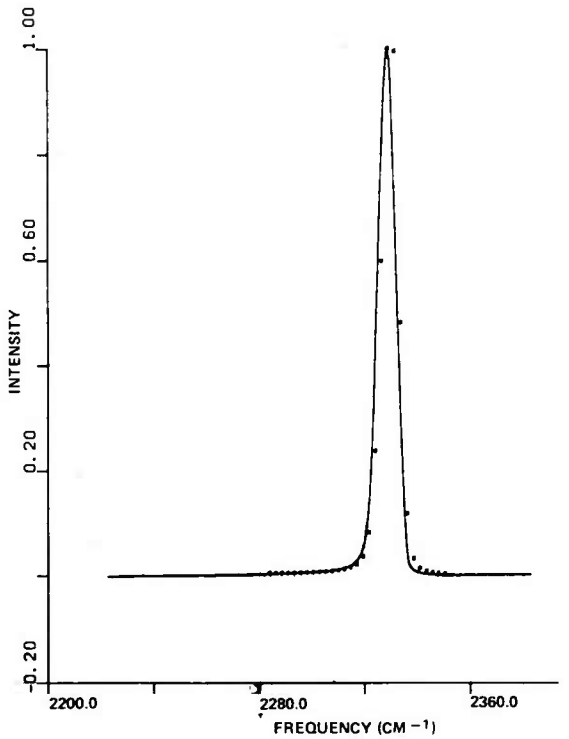


Figure 8. Experimental (.) and calculated $N_2$ CARS spectra of room temperature air (nonplanar CARS)

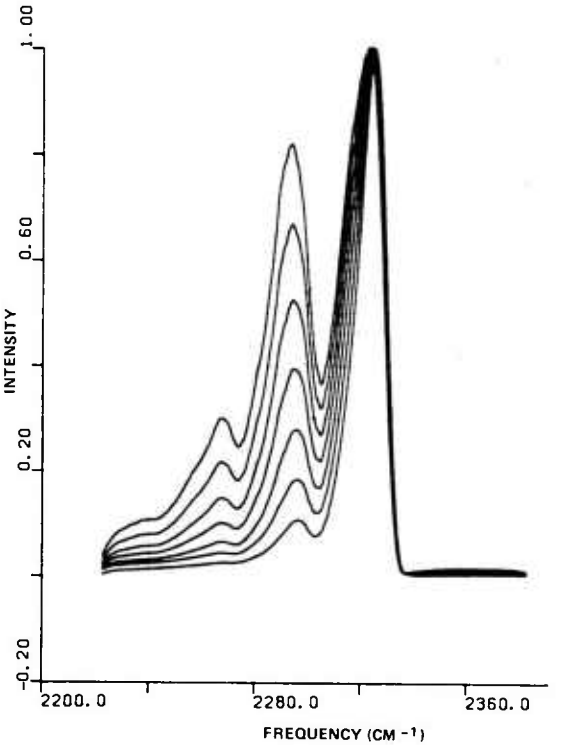


Figure 9. Calculated $N_2$ CARS spectra with temperature varying from 1,500 - 3,000 K at 250 K intervals

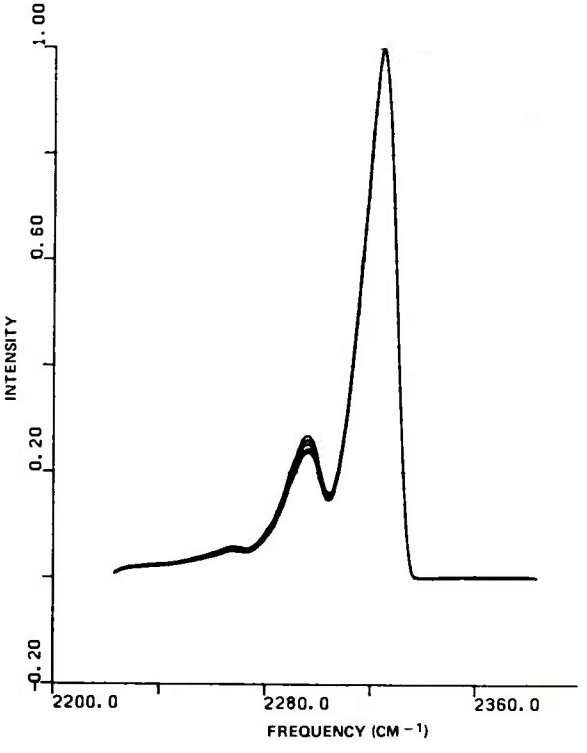


Figure 10. Calculated $N_2$ CARS spectra with temperature varying from 1,900 - 2,000 K at 20 K intervals

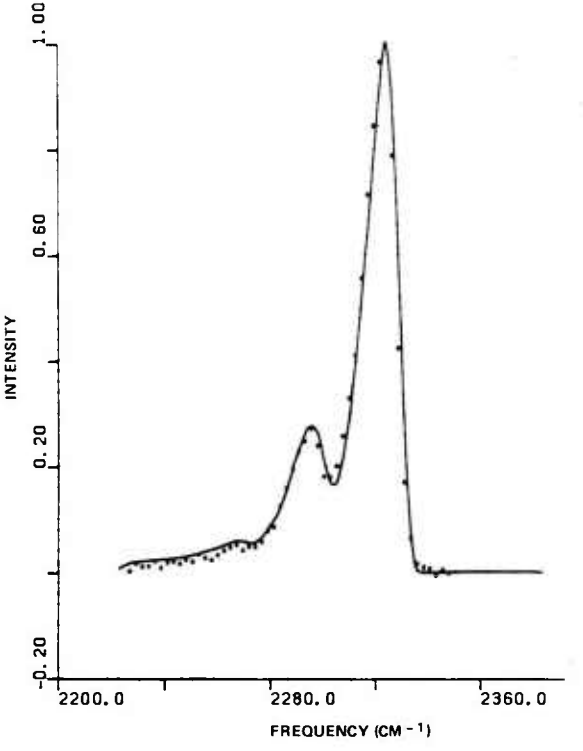


Figure 11. Experimental (.) and calculated $N_2$ CARS spectra for 1.02 equivalence ratio propane/air flame at T = 2,000 K (nonplanar CARS)

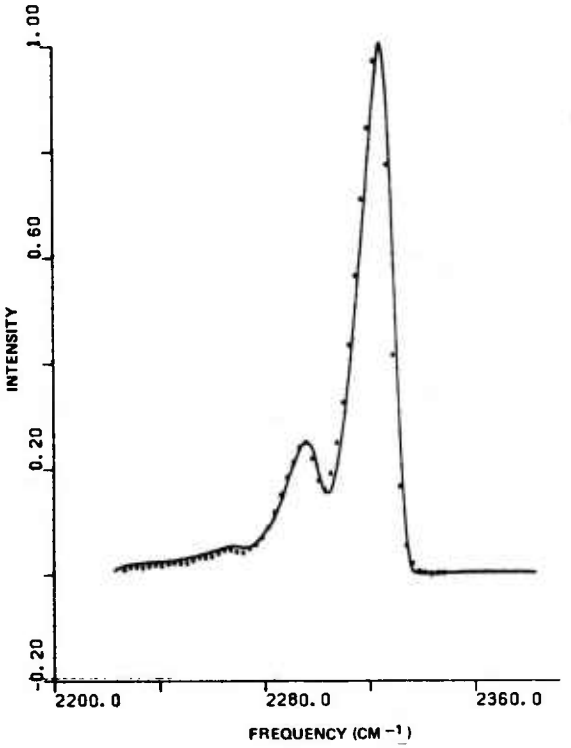


Figure 12. Experimental (.) and calculated $N_2$ CARS spectra for 0.81 equivalence ratio propane/air flame at T = 1,930 K (nonplanar CARS)

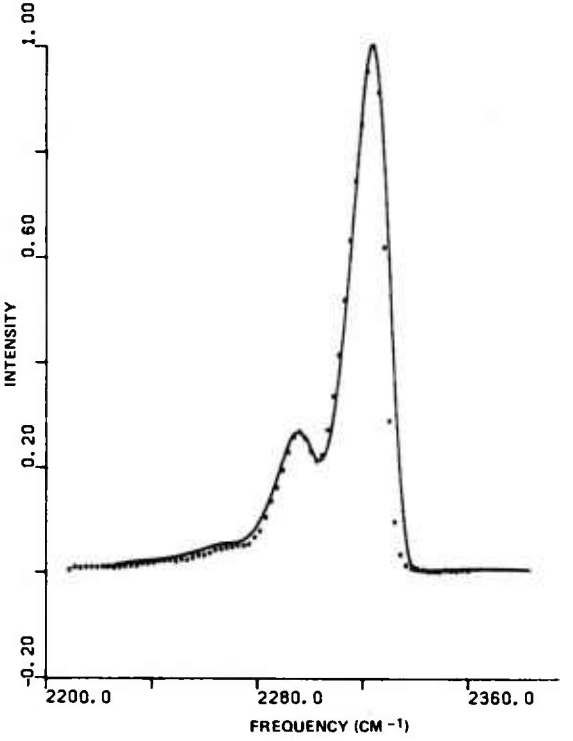


Figure 13. Experimental (.) and calculated $N_2$ CARS spectra for 1.02 equivalence ratio propane air flame at T = 2,020 K (planar CARS)

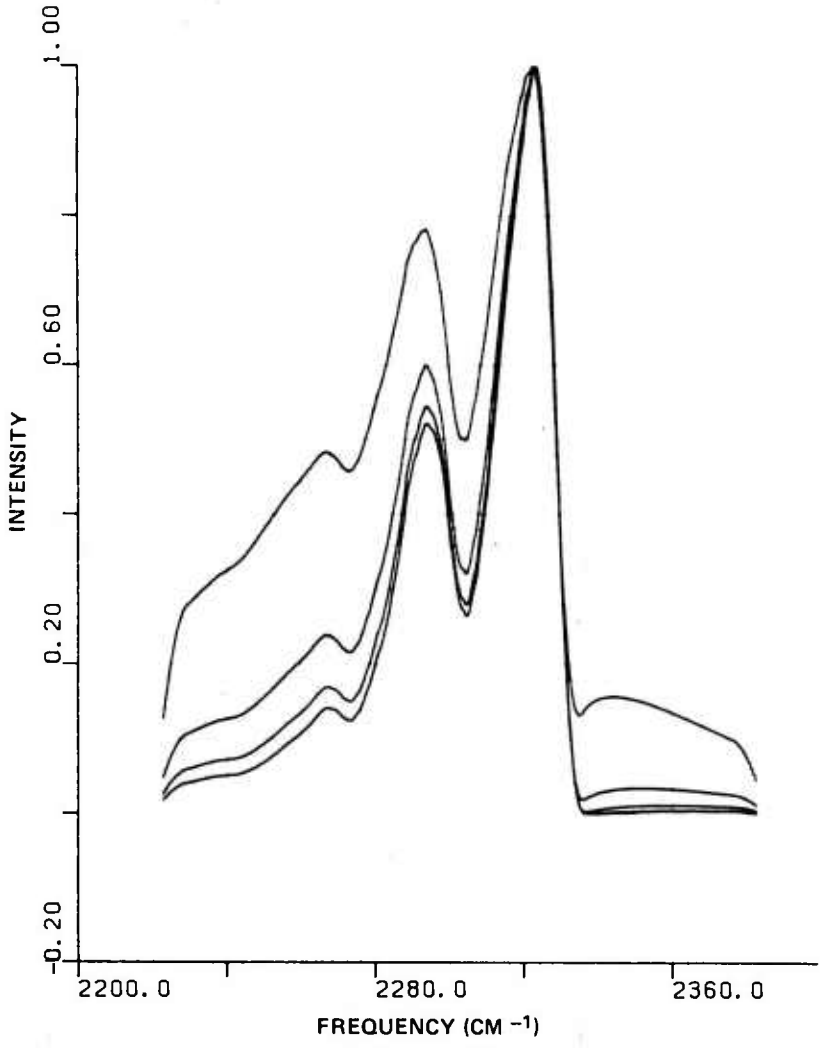


Figure 14. Calculated $N_2$ CARS spectra at 2,500 K for flame products with 25, 50, 70, and 100% of the stoichiometric percentage of air

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