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1

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ATMOSPHERIC ATTENUATION PROPERTIES ASSOCIATED WITH CO_2 LASER RADIATION SPECTRA /119*

Rao Ruizhong* Wang Junbo Yue Shixiao

ABSTRACT In August 1986, in Chengdu city, we did on-the-spot measurements of attenuation in the atmosphere associated with 40 spectral lines of CO_2 laser radiation within oscillation bands 00 °1 - 10 °O and 00 °1 - 02 °O. This article gives general values for various spectral line attenuation coefficients. In conjunction with this, it describes attenuation characteristics. Under the specific conditions of the Chengdu area in August, water vapor absorption and gas aerosol particle absorption along with scattering form the principal components of attenuation. Attenuation coefficients measured in association with various spectral lines can supply beneficial references for CO_2 laser atmospheric applications.

I. INTRODUCTION

Research on the actual characteristics associated with atmospheric propogation of CO_2 lasers, during a relatively long period of time, has principally concentrated on P(20) spectra 00 °1 - 10 °O oscillation bands. In the last few years, people have already done, in the laboratory, relatively broad research [1] on absorption associated with CO_2 laser radiation spectra from such pollutant gases in air as carbon dioxide gas, ozone, as well as water vapor, and so on. However, related studies associated with actual atmospheric attenuation of CO_2 laser radiation spectra are extremely few in number.

In 1978, the American Hanley and others, at White Sands Missile Range, did measurements of atmospheric transmission rates associated with lasers including He-Ne, Nd-YAG, DF, and CO_2 , etc [2]. The experiments in question proved the actual existence in

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

the atmosphere of strong absorption peaks associated with CO_2 laser radiation. Looking at it from the results given, experimental ambient water vapor partial pressures, at their highest, only reached 1440Pa. Gaseous aerosol particles in the atmosphere were extremely rare.

In order to explore actual propogation patterns associated with CO_2 laser radiation in the atmosphere and in order to supply beneficial foundation data for atmospheric applications of CO_2 lasers, in August, 1986, in the eastern suburbs of Chengdu city, we measured attenuations associated with 40 spectral lines within CO_2 laser radiation in the atmosphere. In experimental systems, use was made of acousto-optical modulators to split beams in order to monitor laser transmission powers, eliminating the influence of output power fluctuations. Special climatic characteristics of the experiments were that relative humidity in the Sichuan basin is great and August air temperatures are high.

II. ATTENUATION MECHANISMS

In general weather conditions, various types of gaseous, solid, and liquid materials in the air are capable of being induced as gas molecules and gaseous aerosol particles. Their absorption and scattering of laser radiation constitute the attenuation associated with laser radiation. Attenuation coefficients can be recorded as /120

$$\alpha(\lambda) = \alpha_{sM}(\lambda) + \alpha_{aM}(\lambda) + \alpha_{sA}(\lambda) + \alpha_{aA}(\lambda) \quad (1)$$

In the equation, $\alpha_{sM}(\lambda)$, $\alpha_{aM}(\lambda)$, $\alpha_{sA}(\lambda)$, $\alpha_{aA}(\lambda)$ are, respectively, molecular scattering coefficients when wave lengths are λ, molecular absorption coefficients, gas aerosol scattering coefficients, and gas aerosol absorption coefficients.

1. Molecular Scattering

Wave lengths associated with CO_2 laser radiation in 00 °1 - 10 and OO °1 - 02 °O oscillation bands lie in the range 9 - 11 microns. At this wave length, molecular scattering coefficients are on the order of 10-7km-1 [3]. Compared to attenuation given rise to by other factors, it can be entirely ignored.

2. Molecular Absorption

Molecular absorption includes the two types of separate spectral line absorption and continuous absorption. Relevant mechanisms already possess relatively complete theoretical analyses [4,5]. Research clearly shows that, in air, gases absorbing CO_2 laser radiation are primarily CO_2 gas and water vapor. Due to absorption transitions associated with CO_2 gas and CO_2 laser radiation transitions having a close relationship, the absorptions show themselves as separate spectral absorptions. Water vapor absorption is primarily continuous absorption. However, there exist separate individual spectral absorption peaks [6].

With regard to OO °1 - 10 °O oscillation band P(20) branch lines, widespread option is made for the use of empirical formulae to calculate CO_2 gas and water vapor absorption in air [7,8]

$$\alpha_{CO_2}(10.59) = 1.44 \times 10^{-2}\left(\frac{295}{T}\right)^{1.5}\exp\left(-\frac{2233}{T}\right) \quad (\mathrm{km}^{-1}) \tag{2}$$

$$\alpha_{H_2O}(10.59) = 7.68 \times 10^{-2} p_{H_2O}(P + 193\, p_{H_2O}) \quad (\mathrm{km}^{-1}) \tag{3}$$

In the equations, P is atmospheric pressure strength Pa. T is atmospheric thermodynamic temperature (K). pH_2O is water vapor partial pressure strength (Pa). The relationship between pH_2O

and temperature t(°C) as well as relative humidity R.H. (%) is [8]

$$p_{H_2O} = 6.03 \times R.H. \times 10^{\frac{7.45t}{235+t}} \quad (\mathrm{Pa}) \tag{4}$$

3. Gas Aerosol Particle Absorption and Scattering

If, in unit volumes of atmosphere, gas aerosol particle numbers with radii placed at (r,r+dr) are N(r)dr, then, gas aerosol particle dulling coefficient $\alpha_A(\lambda)$ [equal to $\alpha_{aA}(\lambda)+\alpha_{sA}(\lambda)$] is

$$\alpha_A(\lambda) = \int_0^{\infty} N(r) Q_A(r,\lambda) \pi r^2 dr \tag{5}$$

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$$Q_A(r,\lambda) = Q_{sA}(r,\lambda) + Q_{aA}(\lambda) \tag{6}$$

In the equations, $Q_A(r,\lambda)$, $Q_{sA}(r,\lambda)$, $Q_{aA}(r,\lambda)$ are, respectively, dulling efficiencies, scattering efficiencies, and absorption efficiencies for wave lengths λ and particle radii r.

In air, gas aerosol particle dimensions approach the wave lengths of CO_2 laser light. It is possible to use Mie theory approximation results to analyze the absorption and scattering [10], that is, /121

$$Q_A(r,\lambda) = 2 - 4e^{-\rho \,\mathrm{tg}\beta}\left(\frac{\cos\beta}{\rho}\right)\sin(\rho-\beta) - 4e^{-\rho\,\mathrm{tg}\beta}\left(\frac{\cos\beta}{\rho}\right)^2\cos(\rho-2\beta) + 4\left(\frac{\cos\beta}{\rho}\right)^2\cos(2\beta) \tag{7}$$

$$Q_{aA}(r,\lambda) = 1 + \frac{e^{-4xn'}}{2xn'} + \frac{e^{-4xn'}-1}{8x^2n'^2} \tag{8}$$

In the equations, $x = 2\pi r/\lambda$, $\rho = 2x(n-1)$ $\mathrm{tg}\beta = n'/(n-1)$ n and n' are the real portion and imaginary part of the refraction index associated with gas aerosol particles. Together, it determines the complex indices of refraction associated with the various components making up gas aerosol particles [11]. In conjunction with this, there are influences from atmospheric humidity [12]. In our analytical calculations, n and n' are selected from reference [10] in accordance with dry land gas aerosol models.

The two equations (7) and (8) are approximate Mie theory solutions when $\rho \leqslant 5(n-1)$. When the conditions described above are not satisfied, it is necessary to make corrections as follows [12],

when $5(n-1) < \rho \leqslant 4.08$

$$\begin{bmatrix} Q'_A(r,\lambda) \\ Q'_{aA}(r,\lambda) \end{bmatrix} = \left(1 + \frac{n-1}{n} \cdot \frac{'\rho}{4.08}\right) \begin{bmatrix} Q_A(r,\lambda) \\ Q_{aA}(r,\lambda) \end{bmatrix} \qquad (9)$$

when $\rho > 4.08$,

$$\begin{bmatrix} Q''_A(r,\lambda) \\ Q''_{aA}(r,\lambda) \end{bmatrix} = \left(1 + \frac{n-1}{n} \quad \frac{4.08}{\rho}\right) \begin{bmatrix} Q_A(r,\lambda) \\ Q_{aA}(r,\lambda) \end{bmatrix} \qquad (10)$$

III. EXPERIMENTAL SYSTEMS

Experimental systems include two sections--sending and receiving. Light transmission distance in the atmosphere is 350m. Height above ground is 35m. There are under pad surfaces which fluctuate in height (buildings). Fig.1 is the system line and block diagram.

At transmission terminals, the CO_2 laser devices used are capable of selecting out 40 spectral lines within 00 °1 - 10 °0 and 00 °1 - 02 °0 oscillation bands. Output light goes through acousto-optical modulators, splitting beams. In conjunction with this, modulation forms AC signals. Among them, one diffracted beam of light is used in order to monitor laser light output power. Going through detector probes, and, in conjunction with that, amplification by amplifiers, it is then sent to receiving terminals by radio telemetry transmitter. Going through A/D convertors, it is changed into digital signals and imputed into the computer.

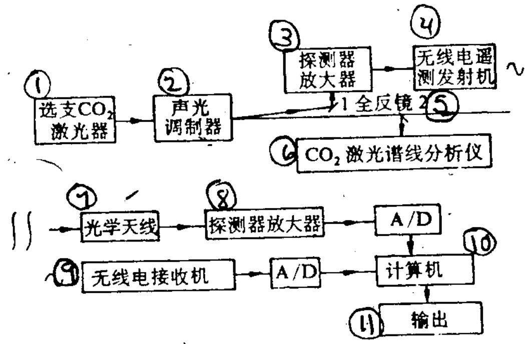

Fig.1 Experimental System Line and Block Diagram

Key: (1) Branch Selecting CO_2 Laser Device (2) Acousto-Optical Modulator (3) Detector Amplifier (4) Radio Telemetry Transmitter (5) Full Reflection Mirror (6) CO_2 Laser Spectrum Analyzer (7) Optical Antenna (8) Detector Amplifier
(9) Radio Receiver (10) Computer (11) Output

/122

Another beam is used in propogation. After going through the atmosphere, it is gathered by an optical antenna onto heat release electric detectors and changed into electric signals. After that, it goes through amplifiers and is amplified. By A/D convertors, it is turned into digital signals and imputed into the computer. The two signal paths go through computer processing. In real time, the status of laser attenuation is obtained. Full reflection mirror 2 is capable of being turned. Its function is that, when it is placed in a certain location, it is used to input propagated light beams into the CO_2 laser spectrum analyzer. In this way, it is then possible to monitor laser spectra. After it moves aside from this position, light beams can then propagate normally.

At the same time as measuring spectral line attenuation, we also recorded several types of meteorological parameters. In conjunction with this, use was made of an 18 track optical particle counter to measure atmospheric gas aerosol particle spectral distribution N(r). During the whole experimental process, temperatures were 19 °C - 36 °C. Relative humidity varied from 40% - 96%. Pressures were relatively low and changes were relatively small. There were slight increases at the end of the month. At the lowest times, they were 94.53 x 103 Pa. At the highest times, they were 95.86 x 103 Pa. The experimental period met with rainy weather.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

From the beginning of August to the end of August, we measured attenuations associated with a total of four P branch and R branch sets of CO_2 laser radiations in the 00 °1 - 10 °C and 00 °1 - 02 °0 oscillation bands--approximately 40 spectral lines. Fig.2 to Fig.5, respectively, are displays of typical data associated with these four sets of spectral attenuation coefficients. As far as the experimental period is concerned, the attenuations associated with the first three sets of spectra each have stable mutual relationships. However, the fourth set shows irregular variations.

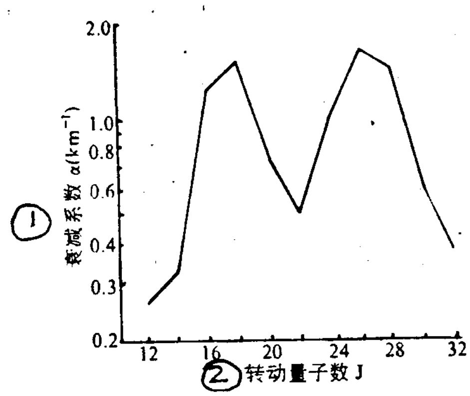

Fig.2 Typical Attenuation Coefficients Associated with 00 °1 - 10 °0 Band P Branch Spectra

Key: (1) Attenuation Coefficient (2) Rotational Quantum Number

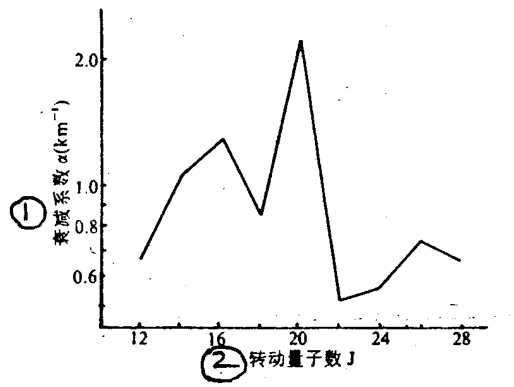

Fig.3 Typical Attenuation Coefficients Associated with 00 °1 - 10 °0 Band R Branch Spectra

Key: (1) Attenuation Coefficient (2) Rotational Quantum Number

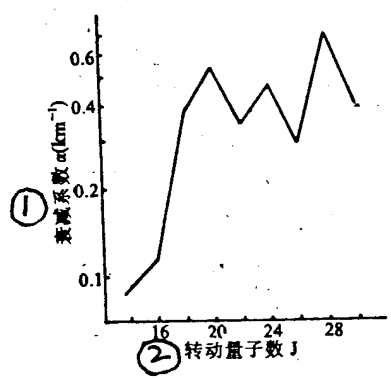

Fig.4 Typical Attenuation Coefficients Associated with 00 °1 - 02 °0 Band P Branch Spectra

Key: (1) Attenuation Coefficient (2) Rotational Quantum Number

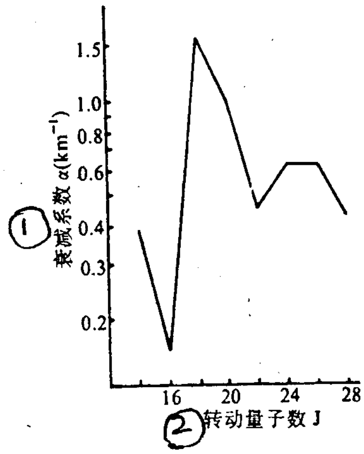

Fig.5 Typical Attenuation Coefficients Associated with 00 °1 - 02 °0 Band R Branch Spectra

Key: (1) Attenuation Coefficient (2) Rotational Quantum Number

From measured attenuation coefficients (see Fig.2 to Fig.5), it is possible to know that spectral attenuation possesses the characteristics described below. In the 00 °1 - 10 °0 band, attenuations in spectra in the vicinity of P(22) are the smallest. However, P(18) and P(26) attenuations reach maximums. In this band, R(20) possesses attenuations far larger than those associated with other spectra. This is in line with the results in references [2] and [6]. In the 00 °1 - 02 °0 band, P(28) attenuations are the largest in the P branch. In the R branch of this band, due to instability in the relationships between the various spectral attenuations, there are no clear characteristics. The causes await further analysis.

Eliminating the circumstance of rainy weather, under average general weather conditions, as far as attenuation coefficients associated with the various spectra are concerned, it is possible to obtain mean atmospheric attenuation values for CO_2 laser radiation spectra in the Chengdu area in August 1986. These are set out in Table 1.

TABLE 1 AVERAGE ATTENUATION VALUES ASSOCIATED WITH CO_2 LASER RADIATION SPECTRA (CHENGDU, AUGUST 1986)

	00 °1 — 02 °0		00 °1— 10 °0	
(1) 谱 线	λ (μ m)	α (km⁻¹)	λ (μ m)	α (km⁻¹)
R (28)	9.229	0.73	10.195	0.70
R (26)	9.239	0.82	10.207	0.80
R (24)	9.250	1.10	10.220	0.59
R (22)	9.260	0.88	10.233	0.58
R (20)	9.271	1.07	10.247	2.32
R (18)	9.282	1.04	10.260	0.72
R (16)	9.293	0.32	10.275	1.05
R (14)	9.305	0.39	10.298	0.96
R (12)	9.317	0.15	10.304	0.62
P (12)	9.448		10.513	0.20
P (14)	9.504	0.16	10.532	0.41
P (16)	9.519	0.22	10.551	1.00
P (18)	9.536	0.30	10.571	1.18
P (20)	9.552	0.70	10.591	0.92
P (22)	9.569	0.66	10.611	0.56
P (24)	9.586	0.70	10.632	0.65
P (26)	9.603	0.53	10.653	1.20
P (28)	9.621	0.87	10.675	1.05
P (30)	9.639	0.46	10.696	0.54
P (32)	9.657		10.719	0.42

Key: (1) Spectrum

Making use, in experimental processes, of simultaneous recordings of meteorological parameters and gas aerosol particle spectra N(r), calculations were done, in accordance with the formulae described above, of various types of dulling factors for 00 °1 - 10 °0 oscillation band P(20) spectral attenuation. In conjunction with this, comparisons were made with experimental results. Table 2 sets out nine sets of data which agree relatively well from among fifteen 00 °1 - 10 °0 band P(20) branch spectra data sets. The reason the other data do not agree well is primarily that, under high humidity conditions, particle refractive indices were not produced accurately. A full analysis of dulling characteristics associated with related gas aerosol particles is just under way.

/124

In measurement processes, due to the fact that spectral powers are relatively low at the two ends of the various spectrum sets, the measurement errors are slightly larger than others. In experimental data as a whole, maximum relative errors are not greater than 18%. With regard to attenuation values greater than $1.0km^{-1}$, errors are smaller than 8%.

TABLE 2 MEASURED VALUES ASSOCIATED WITH ATTENUATION COEFFICIENTS FOR 00 °1 - 10 °0 Band P(20)

1 组 次	1	2	3	4	5	6	7	8	9
T(℃)	32	32	31.5	31	32	27	32	25.5	31.5
P(Pa)	9.46×10^4	9.46×10^4	9.47×10^4	9.49×10^4	9.50×10^4	9.50×10^4	9.46×10^4	9.50×10^4	9.50×10^4
$R\cdot H$.(%)	55	59	58	80	59	78	59	85	60
α_{CO_2}	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.08	0.09
α_{H_2O}	0.38	0.43	0.39	0.68	0.43	0.42	0.43	0.42	0.42
α_A	0.17	0.24	0.24	0.24	0.29	0.72	0.39	0.36	0.30
α^*分析 1	0.64	0.76	0.72	1.01	0.81	1.22	0.91	0.86	0.81
α测量 2	0.62	0.75	0.80	1.08	0.87	1.36	0.95	0.84	0.79
η^+	3.2%	1.3%	10.0 %	6.5%	6.9%	10.3%	4.2%	2.4%	2.5 %

* $\alpha_{分析}=\alpha_{CO_2}+\alpha_{H_2O}+\alpha_A$ (km^{-1}). + $\eta=|\alpha_{分析}-\alpha_{测量}|/\alpha_{测量}$

1 1 2 2

Key: (1) Set (2) Analysis (3) Measurement

V. CONCLUSIONS

Atmospheric attenuation associated with CO_2 laser radiation spectra comes primarily from molecular absorption as well as absorption and scattering associated with gas aerosol particles. Molecular scattering includes CO_2 and water vapor peak value spectral absorption as well as water vapor continuous absorption. The high relative humidity in the Sichuan basin and August high temperatures determined water vapor absorption and gas aerosol particle attenuation. In atmospheric attenuation associated with CO_2 laser radiation spectra, these occupy the leading position. Water vapor continuous absorption, slow changes in gas aerosol particle dulling following variations in wave length, as well as absorption peaks associated with water vapor and carbon dioxide along with separate spectra determined relative attenuation differences between spectra. Changes in temperature, humidity, and gas aerosol particle spectral distribution determined changes in attenuation at different instants.

Attenuations among spectra in the vicinity of 00 1 - 10 °0 band P(22) are the smallest. They are smaller than P(20) averages by 0.4km^{-1}. Because of this, it is appropriate to use it to act as the light source associated with CO_2 laser atmospheric communications. Attenuations associated with 00 °1 - 10 °0 band R(20) and 00 °1 - 02 °0 band P(28) are much larger compared to spectra in the vicinity. Due to their being located on water vapor absorption peaks, the result is that it is possible for them to act as light sources for water vapor and related difference absorption laser radar systems. Other data is capable of supplying atmospheric attenuation references--making precise determinations in the 9-11 micron range--for CO_2 laser atmospheric applications.

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/125

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