New CW CO_2 Laser Lines: The 9-μm Hot Band

K. M. Evenson, Che-Chung Chou, B. W. Bach, and K. G. Bach

***Abstract*—We have made what we think is the first observation of the oscillation of the 9-μm hot-band lines $01^11 \rightarrow [11^10, 03^10]_{II}$ of CO_2. We have observed 40 lines with a maximum power of 8 W. They will provide a new source of laser radiation for spectroscopy. The set of lines has been positively identified by directly measuring the frequencies of two of the lines with a heterodyne technique using a CO_2 laser standard.**

IN order to obtain sequence band CO_2 laser lines, we assembled a grating-coupled laser using a 150-line/mm grating. The grating was specially blazed [1] to provide approximately 2% output coupling in zero order from 9 to 11 μm.

The 1.5-m-long laser has a 1.34-m discharge and an internal diameter of 13.5 mm, which should exhibit less than 0.5% round-trip diffraction loss. We used a ribbed tube with 1.25-mm ribs spaced every 15 mm. We started using the ribbed tube to promote turbulent flow and hoped to increase wall collisions and hence the gain [2]. These ribs did not significantly increase the gain, but did increase the effective resolution of the grating by eliminating waveguide modes. We used a mixture of 12% N_2, 10% CO_2, and 78% He at a total pressure of about 1.9 kPa (14 torr). In this laser we have obtained CW oscillation on all regular CO_2 laser lines from R(62) to P(62), including the R(0) lines, many of the 10.8-μm hot-band lines, many of the 10- μm sequence-band lines, and, surprisingly, a series of lines between the regular 9-μm lines that were not in the predicted positions of the sequence lines. The power maximized on the new lines at a current of 70 mA.

In order to obtain more resolution and verify that these lines are not sequence-band lines, we substituted a 171-line/mm grating [1] with a similar 2% coupling. We then observed these new lines more clearly. We identified three possible transitions: $00^02 \rightarrow [10^01, 02^01]_{II}, 00^03 \rightarrow [10^02, 02^02]_{II}$, and $01^11 \rightarrow [11^10, 03^10]_{II}$, and they are shown in Fig. 1. The former two are the first and second 9-μm sequence bands, and the last one is the 9-μm hot band whose wavelengths have been measured from the emission from a CO_2 discharge with a spectrometer [3]. We calculated their transition frequencies by using the molecule constants given by Rothman in 1986 [4]. The positions of the strongest of our lasing lines agreed with

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K. M. Evenson and C.-C. Chou are with the Time & Frequency Division, National Institute of Standards and Technology, Boulder, CO 80303 USA. C.-C. Chou's permanent address is the Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 30043, Republic of China.
B. W. Bach and K. G. Bach are with Hyperfine Inc., Boulder, CO USA 80301.
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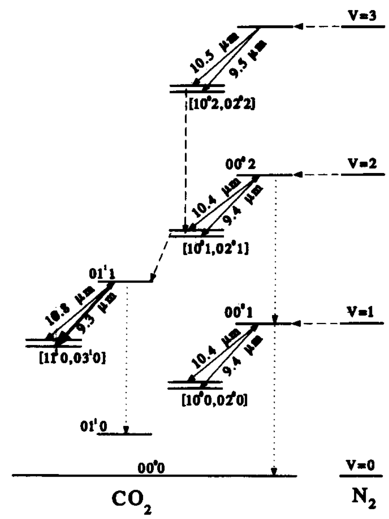

Fig. 1. Simplified vibrational energy level diagram of the CO_2 and N_2 molecules showing the new lasing band by the extra heavy arrow ($01^11 \rightarrow 11^10, 03^10_{II}$). The dotted lines are the 4.3-μm fluorescing emissions used to lock the laser to line center. The dashed lines represent possible excitation paths for populating the lasing levels.

those calculated for the hot bands, and the lines remaining coincided with the sequence-band lines. The positions were checked by simply rotating the grating and plotting the laser output versus the grating position, as is shown in Fig. 2. By comparing calculated frequencies with the grating scanning chart, we found that 40 of the lines were from the 9-μm hot band, and 16 lines from the 9-μm sequence bands.

To confirm our identification, we chose the doublet between 9P(34) and 9P(36), shown in Fig. 1, for a heterodyne frequency measurement with the 9P(34) radiation from another CO_2 laser. According to our identification, the doublet should be the P(42) and P(43) lines of the 9- μm hot band. Their calculated frequencies are 30 960 164 MHz and 30 948 765 MHz, respectively. The frequency measurements were made by heterodyning the reference line with each of the doublet lines using a MIM diode. In each frequency measurement, we tuned each laser to the peak of its gain profile. Beat frequencies were generated from the two lasers and a microwave synthesizer (the second harmonic of the microwave radiation was generated in the MIM diode). The beat frequencies were measured with a spectrum analyzer. The lasers were set to the tops of their respective gain curves (with an uncertainty of a few megahertz); the molecular constants permit an accuracy of about 10 MHz in the calculated frequencies. The results,

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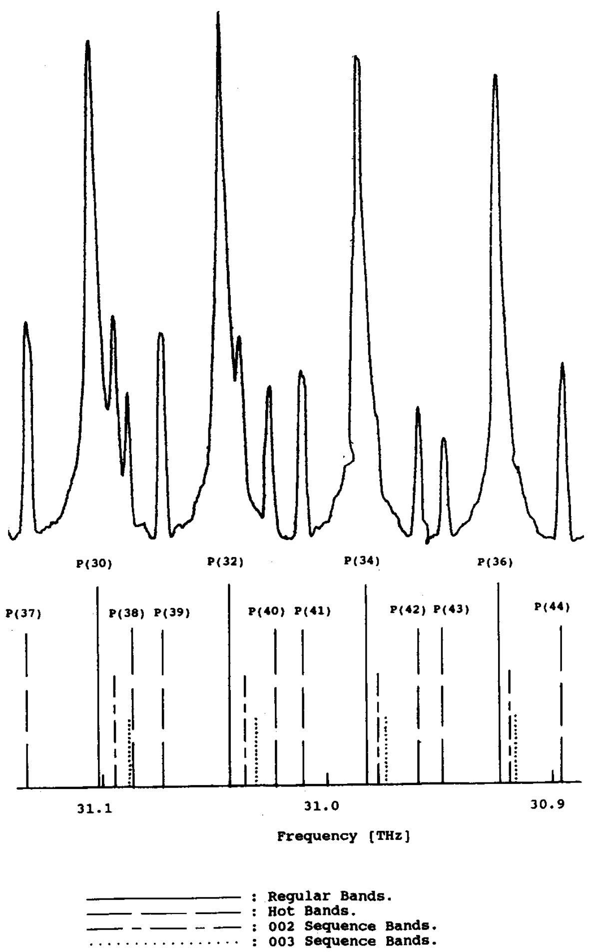

Fig. 2. Laser output power versus grating angle. The line identification was made using the constants from [4].

TABLE I
RESULTS OF FREQUENCY MEASUREMENTS (MHz)

Identification	Predicted Frequency	Observed New Frequency	Observed minus Predicted
REGII P(34)	30 983 193	—	—
002II P(31)	30 977 650	—	—
003II P(28)	30 974 158	—	—
HOTII P(42)	30 960 164	30 960 160	−4
HOTII P(43)	30 948 765	30 948 775	10
REGII P(36)	30 922 917	—	—

shown in Table I, are in good agreement with the calculation within these uncertainties; thus, we have confirmed our identification of these lines by this direct frequency measurement.

These hot-band lines will, almost certainly, serve as pump lines for many new far-infrared lasing lines since most methanol and all difluoromethane lines are pumped at 9 μm. They will also form a new set of standard frequencies at 9 μm since they can be frequency stabilized using the saturated 4.3-μm fluorescence of CO_2 shown in Fig. 1 [5]. The frequencies of many of the 10-μm hot-band lines have been line-center stabilized and accurately measured using this method [6], [7]. We are now also using this method to frequency-stabilize the new lines and are measuring their frequencies.

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