Hydrazine—an excellent optically pumped far-infrared lasing gas: review

E. C. C. Vasconcellos and S. C. Zerbetto

Instituto de Física "Gleb Wataghin," Departamento de Electrônica Quântica, Universidade Estadual de Campinas, 13083-970 Campinas, São Paulo, Brazil

L. R. Zink and K. M. Evenson

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303-3328

Received November 19, 1997; revised manuscript received March 18, 1998

We summarize the 194 far-infrared lasing lines of hydrazine: 7 new lines, 144 lines that we reported recently, and 43 lines reported by other authors. Fewer than 5% of the 43 previously reported lines had wavelengths shorter than 200 μm, but 82% of our 134 lines (127 and 7 new), discovered in cw $^{12}C^{16}O_2$-laser-pumped hydrazine, were shorter than 200 μm; the shortest was at 49.2 μm. Of the 194 lines now known in hydrazine, 150 have been frequency measured. We present the pump line, the pump offset from the CO_2 line center, the far-infrared wavelength and frequency, the optimum pressure, the relative intensity, and the relative polarization of each line. © 1998 Optical Society of America [S0740-3224(98)03307-4]

OCIS codes: 140.3070, 140.5560.

1. INTRODUCTION

Until recently hydrazine (N_2H_4), when it was optically pumped by a $^{12}C^{16}O_2$ cw laser, had just 30 known far-infrared (FIR) laser lines, most with wavelengths longer than 200 μm. In the past few years, we discovered 134 new far-infrared laser lines by optically pumping hydrazine with a cw $^{12}C^{16}O_2$ laser and 17 new far-infrared laser lines by optically pumping hydrazine with an $^{14}N_2{}^{16}O$ laser. Unlike the previously known hydrazine laser lines, most of these new lines have wavelengths shorter than 200 μm. We also measured the frequencies of 150 laser lines plus the frequencies of the doublets of 6 lines. Optimum pressure, relative polarization, relative strength, and pump offset frequency from line center were also determined for most of the lines.

Although most of these measurements have been reported before,[1–9] the last summary of hydrazine laser lines[6] listed only 68 lines and did not report pump offset, polarization, intensity, or pressure. Inasmuch as we thoroughly examined every $^{12}C^{16}O_2$ laser pump line, found 7 new lines, discovered a total of 110 lines with wavelengths less than 200 μm, and did some preliminary studies of the $^{14}N_2{}^{16}O$ laser as a pump, we are now summarizing our work. The 17 new $^{14}N_2{}^{16}O$ laser-pumped lines[9] quadruple the number of known hydrazine FIR lines pumped by this source.[10] Jones *et al.*[10] also reported seven N_2H_4 lines pumped by CO_2 isotope lasers. We have not done any research with these sources.

2. LASER DESCRIPTION

The CO_2 pump laser uses a 1.5-m-long, high-Q Fabry–Perot resonator. The key element in this laser is a high-resolution grating. This grating selects the CO_2 laser transition and also couples out the laser radiation in the zeroth order. By using gratings with different coupling percentages, we are able to cover the complete range of the normal CO_2 laser bands with as much as 40 W of power and also have many sequence-band and hot-band lines oscillating with as much as 20 W. A more comprehensive description of this laser design can be found in Ref. 11. The N_2O laser is of the same design as the CO_2 laser, but the cavity and the discharge lengths were extended 0.5 m to increase the power.[12]

Two FIR lasers were used for these measurements. The first is a 2-m-long, metal-dielectric waveguide laser.[13] It has two flat end mirrors. CO_2 pump radiation is coupled into the laser through a hole in one of these end mirrors for longitudinal pumping. A small 45° polished copper mirror near this end couples out a fraction of the FIR radiation. The other end mirror is mounted upon a movable micrometer to tune the cavity into resonance with the FIR radiation. A Brewster-angled silicon output window transmits most of the FIR radiation and blocks most of the CO_2 radiation. The FIR radiation is detected with either a thermocouple or a metal–insulator–metal (MIM) diode.

The second FIR laser has a 35-mm-diameter, 2-m-long Pyrex tube. At the ends of this tube are two mirrors, one a flat copper mirror and the other a 4-m-radius gold-coated mirror mounted upon a movable micrometer. The hydrazine is longitudinally pumped by CO_2 radiation in a *V* configuration. The CO_2 laser is focused through a 5-mm hole in the flat mirror that is 16 mm above the mirror center. The pump radiation strikes the curved mirror in the center and is then refocused to strike the flat mirror 16 mm below the center. FIR power is coupled out and detected in the same way as was done for the waveguide laser. This laser favors short wavelengths. Its calculated loss is less than 0.5% for wavelengths less than 150 μm.[14]

3. MEASUREMENTS

When searching for new laser lines we first look for absorption of the $^{12}C^{16}O_2$ pump radiation by monitoring the photoacoustic signal from a microphone mounted inside the FIR laser cavity. Optimum photoacoustic signals occur near 650–1300 Pa of hydrazine. Once an absorption signal is found, we search for FIR emission by lowering the hydrazine pressure and simultaneously tuning the FIR cavity length and the pump-laser gain curve to determine the pump offset from the $^{12}C^{16}O_2$ gain maximum. Once a FIR laser signal is detected, the pressure, the output coupling, and the pump offset are adjusted to optimize the signal. In this FIR laser, the polarization relative to the pump polarization is measured. A scan of the laser modes is recorded as a function of FIR cavity length, which gives a first measurement of the number of FIR lines that are lasing and their wavelengths. Finally, measuring the difference in cavity length among 20 laser modes (10 λ) gives a wavelength value accurate to ~0.1%. This process is repeated for every FIR laser line.

A. Frequency Measurements

We determine the FIR laser frequency by heterodyning it with a known frequency; in our case the FIR radiation is mixed in a MIM diode with radiation from two reference CO_2 lasers and a microwave synthesizer. The diode generates frequencies of various mixing orders among these four sources. In our case

$$\delta\nu = \nu_{\mathrm{FIR}} - n|\nu_1 - \nu_2| \pm m\nu_m, \qquad (1)$$

where $\delta\nu$ is the rf beat frequency generated in the diode, ν_{FIR} is the FIR laser frequency, ν_1 and ν_2 are the CO_2 laser frequencies, and ν_m is the microwave frequency. The integers n and m are the mixing order of each component. Once $\delta\nu$ is measured and the values and the sign of the mixing components are determined, the FIR laser frequency can be calculated. Inguscio *et al.*[3] have described this and other frequency-measurement techniques.

The beat note $\delta\nu$ from the MIM diode is amplified and observed with a spectrum analyzer. We then tune the FIR laser across its gain curve and map out the changing amplitude of $\delta\nu$, using a peak hold feature in the spectrum analyzer. The center of this beat note is then measured with a marker frequency. Observing this beat note as each of the four radiations is changed gives the values and signs of n and m. For all measurements here $n = 1, 2$ and $m = 1, 2$. The CO_2 reference frequencies and the microwave frequency are chosen to give $\delta\nu$ within the 1.5-GHz bandwidth of our amplifier and spectrum analyzer.

The CO_2 reference lasers are frequency stabilized within ±10 kHz, and their frequencies are known to an accuracy of 2.5 kHz. The microwave source frequency is also accurate within 10 Hz. The main uncertainty comes from setting the FIR laser to the center of its gain curve. We generally measure each frequency five times or more and report the average measurement. Our 1σ uncertainty is 2×10^{-7} times the frequency (the accuracy of the synthesized reference is ~15 kHz, or 5×10^{-9} at 3 THz).

B. Frequency Offset Measurements

Pump-frequency offset (the difference between the absorption frequency and the CO_2 laser line center frequency) measurements are important for assigning these FIR laser transitions. Measuring the offset is a simple matter of setting the pump frequency for maximum FIR power and then mixing, in a MIM diode, some of the pump radiation with a reference laser locked to the appropriate line center. As with the FIR frequency measurements, the diode generates between the two laser frequencies a beat note that is measured as above. Inasmuch as some residual pump radiation is coupled out of the FIR laser along with the FIR radiation, we remove

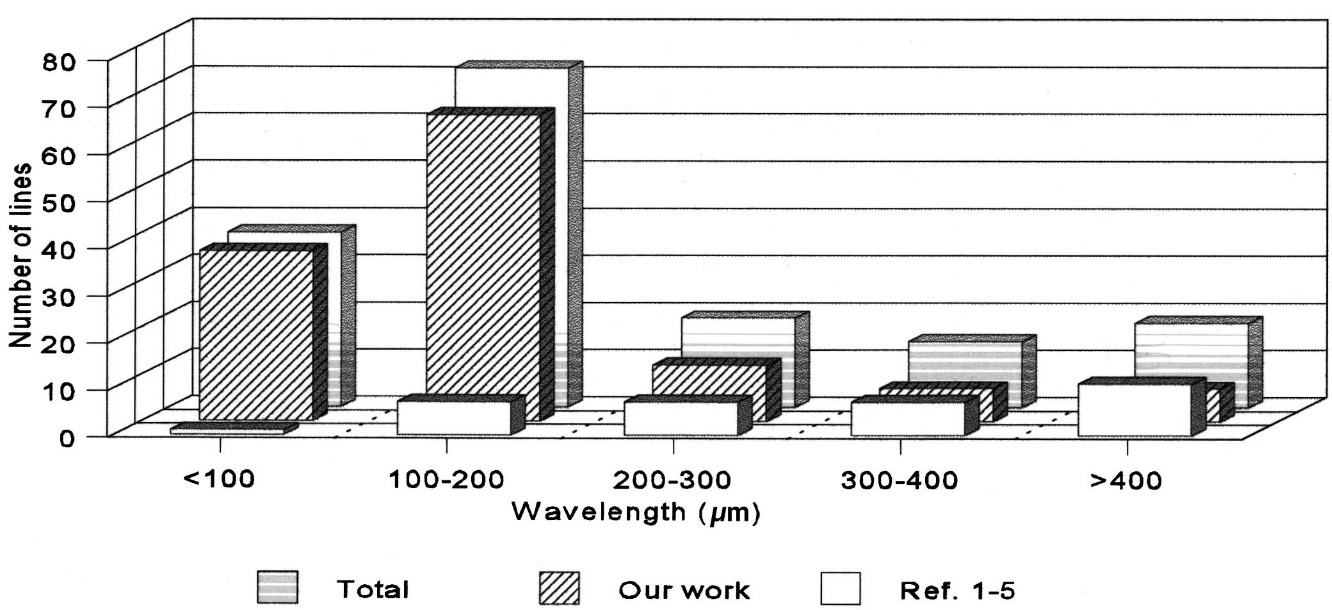

Fig. 1. Wavelength distribution of N_2H_4 FIR laser lines pumped by $^{12}C^{16}O_2$.

Table 1. Summary of the Hydrazine FIR Laser Lines Pumped by a $^{12}C^{16}O_2$ Laser

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Wavelength (μm)[b]	Pressure [Pa (mTorr)]	Relative Intensity[c]	Relative Polarization	Offset (MHz)	Ref.
$9R(52)$	4 463 894.4	67.159	53(400)	W	∥	43	8
$9R(50)$	4 553 228.0	65.842	53(400)	M	∥	−9	7
$9R(48)$	574 117.3	522.180	7(50)	W			6
$9R(46)$	1 945 888.1	154.065	11(80)	M	∥	−2	7
		454.7	33(250)	M	∥	−2	7
$9R(42)$	858 156.2	349.345	20(150)	VS	⊥		6, 7
$9R(36)$	2 950 180.8	101.618	27(200)	S	∥	−38	7
$9R(34)$	1 055 803.2	283.947	13(100)	VS	∥		7
$9R(26)$	916 511.7	327.102	20(150)	S	∥	−13	1, 7
$9R(18)$	812 750.0	368.862	27(200)	M			3
$9R(14)$	3 497 481.1	85.717	27(200)	S	∥	−50	7
$9R(12)$	3 975 563.7	75.409	60(450)	W	∥	35	8
$9R(10)'$	4 104 665.7	73.037	47(350)	W	∥	43	8
$9R(10)''$	1 203 541.3	249.092	20(150)	M	∥	−20	1, 7
$9R(8)$	3 696 638.2	81.099	33(250)	S	∥	−12	7
$9R(4)$	3 918 281.0	76.511	13(100)	M	∥	40	7
		125.7	20(150)	M	∥		7
$9SP(11)$		85.9	13(100)	S	∥		7
$9P(08)$		708.3	20(150)	M	∥		7
$9P(12)'$	904 899.4	331.299	20(150)	S	∥(⊥)		2, 6
$9P(12)''$	903 889.6	331.669	20(150)	S	∥(⊥)		1, 2, 6
$9P(12)'''$	567 925.4	527.873	7(50)	M			2
$9P(14)$	3 317 269.0	90.373	53(400)	VS	∥	−32	7
$9P(16)'$	3 536 744.1	84.765	20(150)	M	∥	8	7
$9P(16)''$	3 304 457.8	90.724	20(150)	S	∥	−45	7
$9SP(13)$	2 884 000.7	103.950	53(400)	VS	∥	−12	7
$9P(20)$	963 731.4	311.075	4(30)	M	∥		1, 2
$9P(20)$		483.5			∥		1
$9P(22)$		73.07					New
	2 510 428.7	119.419	43(320)	W	∥	39	8
$9P(30)$	1 920 424.5	156.107	20(150)	M	∥	28	7
		331.5			∥		1
$9P(32)$	4 058 513.9	73.868	40(300)	S	∥	28	7
$9P(34)$		102.0	53(400)	VS	∥		New
$9P(36)'$	2 946 196.7	101.756	20(150)	M	∥		6
$9P(36)''$	2 225 036.9	134.736	27(200)	W			6
$9P(36)'''$	1 619 248.8	185.143	13(100)	W			6
$9P(46)$	1 866 375.4	160.628	27(200)	VS	∥	−7	7
	960 791.1	312.027	27(200)	VS	∥	−7	6, 7
$9P(50)$	2 104 368.9	142.462	20(150)	VS	∥	43	7
$9P(52)$	2 473 562.9	121.199	27(200)	S	∥	−45	7
$9P(56)$	1 644 081.4	182.346	20(150)	S	∥	−32	7
$10R(54)'$	2 729 129.8	109.849	21(160)	M	∥	−19	7
$10R(54)''$	2 340 717.5	128.077	33(250)	S	∥	19	7
$10R(52)$	2 106 238.3	142.335	43(320)	S	∥	40	7
$10R(50)'$	5 034 814.5	59.544	117(880)	S	∥	−16	7
		61.9	96(720)	M	∥		7
$10R(50)''$	2 638 540.7[d]	113.621	29(220)	S	∥	7	7
	2 638 537.7[d]	113.621	29(220)	S	∥	7	7
	1 635 937.6	183.254	29(220)	M	⊥	7	7
$10R(48)$	2 740 883.2	109.378	40(300)	M	∥	10	7
$10R(44)$	2 651 522.1	113.064	44(330)	S	∥	−22	7
$10R(42)'$	3 551 318.2	84.417	43(320)	M	∥	44	7
$10R(42)''$	3 343 021.8	89.677	33(250)	M	∥	−23	7
$10R(40)$	1 485 618.5	201.796	65(490)	VS	∥	−36	7
$10R(38)$	1 272 681.1	235.559	25(190)	VS	∥		5, 7

(*Table continued*)

Table 1. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Wavelength (μm)[b]	Pressure [Pa (mTorr)]	Relative Intensity[c]	Relative Polarization	Offset (MHz)	Ref.
10R(38)	408 346.7	734.162					3
10R(36)′	2 746 267.9	109.164	25(190)	M	∥	−14	7
10R(36)″	1 868 475.0	160.448	33(250)	S	∥	44	7
	960 791.1	312.027	37(280)	S	⊥	44	7
10R(34)′	2 082 274.2	143.974	40(300)	VS	⊥	41	7
10R(34)″		153.4	29(220)	VS	∥		7
		234.0			∥		1
10R(34)‴	1 371 660.8	218.562	40(300)	VS	∥	44	7
10R(30)	1 132 510.3	264.715	33(250)	S	∥	−10	1, 7
10R(28)	1 955 291.8	153.324	28(210)	S	∥	42	7
10SR(27)	1 860 374.8	161.146	37(280)	S	∥	7	7
10SR(23)′	3 275 035.8	91.359	32(240)	VS	∥	26	7
10SR(23)″	2 743 410.5	109.277	25(190)	VS	∥	−28	7
10SR(23)‴		267.4	32(240)	M	∥	47	7
10R(24)		802.4			∥		1
10R(20)	2 092 854.4	143.246	24(180)	S	⊥		5
		165.0	25(190)		∥		New
	1 132 140.6	264.801	27(200)	S	∥		1, 2
10R(18)′	2 790 942.8	107.416	36(270)	M	∥		7
10R(18)″		116.7	40(300)	M	∥	−33	7
10SR(21)	939 054.3	319.249	27(200)	VS	∥		7
10SR(17)	1 610 436.0	186.156	20(150)	VS	∥	19	7
10HR(14)′	1 977 072.4	151.635	13(100)	M	∥	−30	7
10HR(14)″	1 574 927.0	190.353	13(100)	M	⊥	−8	7
10R(12)		234.12	35(260)		∥		New
10R(12)	995 077.8	301.275	20(150)	S	∥		1, 2
	802 492.8	373.576			⊥		1, 5
10SR(11)	2 381 482.4[d]	125.885	13(100)	S	∥	36	7
	2 381 478.9[d]	125.885	13(100)	S	∥	36	7
	1 510 382.3	198.488	11(80)	W	∥		7
		234.36	13(100)		∥		New
10SR(9)	1 126 495.9	266.128	20(150)	VS	⊥	0	7
	645 737.5	464.264	19(140)	VS	∥	0	7
10R(8)	1 281 625.8	233.916	13(100)	VS	∥		1, 2
	561 773.0[d]	533.654			⊥		1, 5
	561 771.3[d]	533.656			⊥		1, 5
10R(6)	2 565 990.1	116.833	5(40)	M			6
10R(4)	5 116 059.9	58.598	108(810)	M	∥		7
	2 574 085.5	116.466	39(290)	VS	∥	39	7
	1 989 217.5	150.709					5
10P(2)	4 017 213.1	74.627	21(160)	M	∥		7
	1 811 655.9	165.480	23(170)	M	∥	−11	7
10P(4)′		49.2	24(180)	M	∥	−36	7
	3 844 230.0	77.985	23(170)	M	∥	−36	7, 8
10P(4)″	3 319 710.8	90.307	41(310)	S	⊥		7
	2 415 908.4	124.090	39(290)	M	∥		7
	2 098 942.5	142.830	20(150)	M	∥		7
10P(4)‴	2 625 546.4	114.183	28(210)	S	∥	42	7
		186.1	24(180)	W	⊥	42	7
10P(6)′	2 221 963.2	134.922					5
10P(6)″	2 174 579.3	137.862					5
10P(6)‴	1 647 877.4	181.926	20(150)	S	⊥(∥)		2
10P(6)‴		246.5			∥		1
10P(10)	1 880 947.4	159.384	5(40)	W			6
	1 450 431.1	206.692	40(300)	M	∥	37	7

(*Table continued*)

Table 1. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Wavelength (μm)[b]	Pressure [Pa (mTorr)]	Relative Intensity[c]	Relative Polarization	Offset (MHz)	Ref.
	1 907 887.0	157.133	24(180)	M	∥	−43	7
		721.0			∥		1
10*P*(16)′	3 690 723.1	81.229	20(150)	M	⊥		5
	2 923 359.0	102.551	53(400)	S	∥		5
10*P*(16)″	650 207.7	461.072			⊥		1, 2
10*P*(18)′	4 668 834.6	64.211	29(220)	W	∥	−43	8
10*P*(18)″	2 555 898.1	117.294	27(200)	W	∥	26	8
		273.0	13(100)	W	∥		1
10*P*(18)″		372.5			⊥		1
10*P*(20)	3 559 814.8	84.216	67(500)	M	∥	−42	8
10*P*(22)	3 691 269.2	81.217	20(150)	W	∥	31	8
	2 923 138.5	102.558	20(150)	W	∥	31	8
		1007.0			⊥		1
10*P*(24)′	3 676 638.9	81.540	29(220)	M	∥	40	8
10*P*(24)″	2 460 606.8	121.837	27(200)	M	∥	13	8
10*P*(24)‴	1 554 077.8	192.907	15(110)	VS	⊥	−32	1, 2, 6
		336.0			⊥		1
	687 957.4	435.772	7(50)	S	⊥		1, 2
10*P*(26)	3 197 414.3	93.761	29(220)	M	∥	−46	8
10*P*(28)		262.0			⊥		1
10*P*(30)′	3 442 096.1	87.096	13(100)	M	∥	−36	8
10*P*(30)″	2 695 149.6	111.234	13(100)	M	∥	−8	7
10*SP*(29)	2 432 134.3	123.263	27(200)	VS	⊥	−12	8
	1 615 503.5	185.572	20(150)	VS	∥	−12	7
10*P*(32)	2 219 596.6	135.066	19(140)	W	∥	0	8
		795.0			⊥		1
10*SP*(31)	4 722 332.3	63.484	27(200)	M	∥	1	8
	3 559 099.1	84.233	27(200)	M	∥	1	8
10*SP*(33)	5 494 676.8	54.561	27(200)	M	∥	−7	8
10*P*(36)	3 266 508.2	91.778	21(160)	M	∥	−33	8
10*P*(40)	1 241 985.4	241.382	7(50)	M			6
	568 210.2	527.608	7(50)	W			6
10*P*(42)	954 857.6[d]	313.966					6
	954 850.7[d]	313.968					6
	569 599.7[d]	526.321					6
	569 589.7[d]	526.331					6
10*P*(44)		89.5					New
10*P*(44)	3 172 777.9	94.489	27(200)	S			6
10*P*(44)	2 452 677.4	122.231	27(200)	VS			6
10*P*(46)	3 444 748.6	87.029	33(250)	W	⊥	34	8
10*P*(52)	1 860 374.6	161.146		W			6
	1 833 951.7	163.468					6
10*HP*(19)		93.5	43(320)		∥		New
10*P*(54)	2 988 681.8	100.309	28(210)	VS	⊥		6, 8
	1 980 809.4	151.348	11(80)				6
10*HP*(20)	1 573 986.2	190.467	10(75)				6
10*HP*(22)	1 037 179.7	289.046	24(180)	M	⊥		8
10*P*(56)–*HP*(23)	3 896 540.2	76.938	24(180)	VS	∥		8
	1 556 427.9	192.616		VVS			6
	885 606.8	338.516		S			6
10*HP*(24)	2 823 688.6	106.171	13(100)	M			6
10*HP*(24)	1 864 680.0	160.774	10(75)	W			6
10*HP*(25)	1 708 654.6	175.455	19(140)	M	∥		8
10*HP*(29)	3 214 438.5	93.264	33(250)	S	∥		8

(*Table continued*)

Table 1. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Wavelength (μm)[b]	Pressure [Pa (mTorr)]	Relative Intensity[c]	Relative Polarization	Offset (MHz)	Ref.
	1 858 872.0	161.277	7(50)	VS			6
	1 040 932.6	288.004	8(60)	M	∥		6
10 HP (32)	1 282 805.7	233.701	8(60)	S			6
	1 042 133.2	287.672	8(60)	S			6

[a] ′, ″, and ‴ indicate different $^{12}C^{16}O_2$ laser frequency offsets from line center.
[b] Calculated from $c = 299\ 792\ 458$ m/s.
[c] Abbreviations here and in the tables that follow are defined in text.
[d] Doublets.

any CO_2 filters in front of the FIR-measuring MIM and easily perform the measurement. For regular pump lines the reference laser is set to the same laser transitions as the pump line. For hot-band and sequence-band lines the closest regular line is used for the reference, and the difference is made up by a microwave synthesizer. Our pump offset measurements are reproducible within 2 MHz. Our pump laser's free spectral range is ±37.5 MHz from line center, so any offset measurements that are ⩾38 MHz are near the edge of the CO_2 gain curve.

4. RESULTS

We present pump line, FIR frequency and wavelength, optimum pressure, relative strength, relative polarization, pump offset, and reference to the original research-for all the 194 known hydrazine FIR laser lines pumpedby a cw $^{12}C^{16}O_2$ laser, isotopic CO_2 lasers, and a $^{14}N_2{}^{16}O$ laser.

Of the 164 unique FIR laser lines obtained by $^{12}C^{16}O_2$ laser pumping, 135 (82%) have been frequency measured (we count the doublets just once). Twelve lines reported by Dyubko *et al.*[1] have not been frequency measured. We have observed oscillation on only one of these. Our laser favors short-wavelength lines and has so much loss that it will not lase at long wavelengths. Several other unobserved lines from Ref. 1 have been excluded from the table or have been assigned to other pump lines. Of the 17 new FIR laser lines obtained by $^{14}N_2{}^{16}O$ laser pumping, 12 have been frequency measured. We also measured the frequencies of three other previously reported laser lines pumped by an N_2O laser. Of the 23 lines obtained by pumping hydrazine with a $^{14}N_2{}^{16}O$ laser, 65% are now measured in frequency. Hydrazine is probably the molecule with the highest percentage (78%) of frequency-measured laser lines.

Figure 1 shows the wavelength distribution of the $^{12}C^{16}O_2$-laser-pumped hydrazine lines. Of the 164 lines discovered by pumping with the regular $^{12}C^{16}O_2$ laser, 110 have wavelengths shorter than 200 μm. This is an important region for spectroscopy, and a high density of lines at higher frequencies makes hydrazine an important FIR lasing medium. Of the 110 lines below 200 μm pumped by the $^{12}C^{16}O_2$ laser, 108 were discovered in our laboratory. Table 1 is a summary of the 164 laser lines arranged by the CO_2 pump lines. It contains the frequency, wavelength, optimum pressure, relative polarization, relative intensity, pumping offset, and reference for each line. The relative intensities of the laser lines presented in the tables are listed with the references in which they were reported. We use the notation VW (very weak), W (weak), M (medium), S (strong), VS (very strong), and VVS (very, very strong) to denote the relative intensities of the lines. The intensities differ from successive ones by 1 order of magnitude. On our scale the well known 119-μm line of methanol is VVS; the 192.616-μm hydrazine line has the same value. The 312.027-μm line is pumped by two different CO_2 lines, 9*P*(46) and 10*R*(36). The same is true for the 161.146-μm line, which is pumped by two different CO_2 lines, 10*SR*(27) and 10*P*(52). In each case the two pumps populate the same upper lasing level in hydrazine and therefore produce the same FIR lasing line. There are also five doublets, denoted by footnotes in the tables, from CO_2 laser pumping and one doublet from N_2O laser pumping. The doublet separations vary from 2.7 to 10 MHz. This doublet structure could be a real property of hydrazine, as noted in Ref. 5 for the 533.7-μm line, or it could be an artifact of our longitudinal pumping, with the FIR frequency being pulled by pump Doppler pulling, producing two peaks in the FIR gain curve.

Table 2. Summary of the Hydrazine FIR Laser Lines Pumped by Isotopic CO_2 Laser

Laser Pump Line	Wavelength (μm)	Relative Intensity[a]	Ref.
$^{12}C^{18}O_2$			
10*P*(24)	705.0	S	10
$^{13}C^{16}O_2$			
10*P*(18)	219.0	VS	10
10*P*(24)	945.0	S	10
10*P*(30)	289.0	VVS	10
$^{13}C^{18}O_2$			
10*R*(18)	267.0	M	10
10*P*(14)	863.0	M	10
9*P*(14)	195.0	VS	10

[a] The relative intensity estimations in this table do not correlate with ours; they are being reported according to the references in which they can be found.

Table 2 is a summary of the lines observed by Jones *et al.*[10] with isotopic CO_2 lasers. We have excluded a line pumped by the $^{13}C^{18}O_2$ 10*P*(28) laser line, whose wavelength was not measured in that reference. Table 3 summarizes our preliminary study of $^{14}N_2{}^{16}O$-laser-pumped hydrazine. We did not measure the offsets for the

Table 3. Summary of the Hydrazine FIR Laser Lines Pumped by an $^{14}N_2{}^{16}O$ Laser

$^{12}N_2{}^{16}O$ Laser Pump Line[a]	Frequency (MHz)	Wavelength (μm)[b]	Pressure [Pa (mTorr)]	Relative Intensity	$^{14}N_2{}^{16}O$ Power (W)	Ref.
10*R*(38)		339.4	19(140)			9
10*R*(36)		98.0	35(260)	M	3.2	9
10*R*(25)	2 823 287.0	106.186	19(140)	W	5.0	9
10*R*(24)		257.5	15(110)	W	4.2	9
10*R*(11)	906 899.8	330.568	15(110)	W	5.2	10
10*R*(4)	1 369 893.3	218.844	9(70)	W	2.6	9
10*P*(7)	1 371 481.5	218.590	27(200)	M	5.0	10
10*P*(11)	1 858 872.0	161.277	9(70)	W	6.0	9
10*P*(11)		575.0				10
10*P*(15)‴	2 631 380.7	113.930	19(140)	W	5.4	9
10*P*(15)″	1 288 113.7	232.738	7(50)	W	5.8	9
10*P*(15)′	801 069.7	374.240	9(70)	W	5.8	10
10*P*(16)	2 191 609.6[c]	136.791	13(100)	M	6.0	9
	2 191 613.7[c]	136.791	13(100)	M	6.0	9
10*P*(24)	2 485 511.6	120.616	27(200)	M	6.0	9
10*P*(24)		237.0				10
10*P*(26)		114.2	21(160)	M	4.0	9
10*P*(28)		492.4	17(130)	W	5.0	10
10*P*(29)		241.6	16(120)	W	6.0	9
10*P*(30)	1 902 430.3	157.584	8(60)	M	4.0	9
10*P*(34)	1 426 180.2	210.207	7(50)	M	3.8	9
10*P*(34)	1 041 094.2	287.959	13(100)	W	4.4	9
10*P*(32)	3 222 036.9	93.044	24(180)	S	4.0	9
10*P*(45)	2 823 544.5	106.176	23(170)	M	1.8	9

[a] ′, ″, and ‴ indicate different $^{14}N_2{}^{16}O$ laser frequency offsets from line center.
[b] Calculated from $c = 299\,792\,458$ m/s.
[c] Doublets.

Table 4. Summary of the Hydrazine FIR Laser Lines Pumped by a $^{12}C^{16}O_2$ Laser, Sorted by Increasing Wavelength

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Calculated Wavelength (μm)[b]	Calculated Wave Number (cm^{-1})	Pressure [Pa (mTorr)]	Relative Intensity	Relative Polarization	Offset (MHz)	Ref.
10*P*(4)′		49.2		24(180)	M	∥	−36	7
10*SP*(33)	5 494 676.8	54.561	183.2827	27(200)	M	∥	−7	8
10*R*(4)	5 116 059.9	58.598	170.6534	108(810)	M	∥		7
10*R*(50)′	5 034 814.5	59.544	167.9433	117(880)	S	∥	−16	7
10*R*(50)″		61.9		96(720)	M	∥		7
10*SP*(31)	4 722 332.3	63.484	157.5201	27(200)	M	∥	1	8
10*P*(18)′	4 668 834.6	64.211	155.7356	29(220)	W	∥	−43	8
9*R*(50)	4 553 228.0	65.842	151.8793	53(400)	M	∥	−9	7
9*R*(52)	4 463 894.4	67.159	148.8995	53(400)	W	∥	43	8
9*R*(10)′	4 104 665.7	73.037	136.9169	47(350)	W	∥	43	8
9*P*(22)		73.07						New
9*P*(32)	4 058 513.9	73.868	135.3775	40(300)	S	∥	28	7
10*P*(2)	4 017 213.1	74.627	133.9998	21(160)	M	∥		7
9*R*(12)	3 975 563.7	75.409	132.6105	60(450)	W	∥	35	8
9*R*(4)	3 918 281.0	76.511	130.6998	13(100)	M	∥	40	7
10*P*(56)–*HP*(23)	3 896 540.2	76.938	129.9746	24(180)	VS	∥		8
10*P*(4)′	3 844 230.0	77.985	128.2297	23(170)	M	∥	−36	7, 8
9*R*(8)	3 696 638.2	81.099	123.3066	33(250)	S	∥	−12	7
10*P*(22)	3 691 269.2	81.217	123.1275	20(150)	W	∥	31	8
10*P*(16)′	3 690 723.1	81.229	123.1093	20(150)	M	⊥		5
10*P*(24)″	3 676 638.9	81.540	122.6395	29(220)	M	∥	40	8
10*P*(20)	3 559 814.8	84.216	118.7426	67(500)	M	∥	−42	8
10*SP*(31)	3 559 099.1	84.233	118.7188	27(200)	M	∥	1	8
10*R*(42)′	3 551 318.2	84.417	118.4592	43(320)	M	∥	44	7

(*Table continued*)

Table 4. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Calculated Wavelength (μm)[b]	Calculated Wave Number (cm^{-1})	Pressure [Pa (mTorr)]	Relative Intensity	Relative Polarization	Offset (MHz)	Ref.
9P(16)′	3 536 744.1	84.765	117.9731	20(150)	M	∥	8	7
9R(14)	3 497 481.1	85.717	116.6634	27(200)	S	∥	−50	7
9SP(11)		85.9		13(100)	S	∥		7
10P(46)	3 444 748.6	87.029	114.9044	33(250)	W	⊥	34	8
10P(30)′	3 442 096.1	87.096	114.8160	13(100)	M	∥	−36	8
10P(44)		89.5						New
10R(42)″	3 343 021.8	89.677	111.5112	33(250)	M	∥	−23	7
10P(4)″	3 319 710.8	90.307	110.7336	41(310)	S	⊥		7
9P(14)	3 317 269.0	90.373	110.6522	53(400)	VS	∥	−32	7
9P(16)″	3 304 457.8	90.724	110.2248	20(150)	S	∥	−45	7
10SR(23)′	3 275 035.8	91.359	109.2434	32(240)	VS	∥	26	7
10P(36)	3 266 508.2	91.778	108.9590	21(160)	M	∥	−33	8
10HP(29)	3 214 438.5	93.264	107.2221	33(250)	S	∥		8
10HP(19)		93.5		43(320)		∥		New
10P(26)	3 197 414.3	93.761	106.6543	29(220)	M	∥	−46	8
10P(44)	3 172 777.9	94.489	105.8325	27(200)	S			6
10P(54)	2 988 681.8	100.309	99.6917	28(210)	VS	⊥		6, 8
9R(36)	2 950 180.8	101.618	98.4074	27(200)	S	∥	−38	7
9P(36)′	2 946 196.7	101.756	98.2745	20(150)	M	∥		6
9P(34)		102.0		53(400)	VS	∥		New
10P(16)′	2 923 359.0	102.551	97.5128	53(400)	S	∥		5
10P(22)	2 923 138.5	102.558	97.5054	20(150)	W	∥	31	8
9SP(13)	2 884 000.7	103.950	96.1999	53(400)	VS	∥	−12	7
10HP(24)	2 823 688.6	106.171	94.1881	13(100)	M			6
10R(18)′	2 790 942.8	107.416	93.0958	36(270)	M	∥		7
10R(36)′	2 746 267.9	109.164	91.6056	25(190)	M	∥	−14	7
10SR(23)″	2 743 410.5	109.277	91.5103	25(190)	VS	∥	−28	7
10R(48)	2 740 883.2	109.378	91.4260	40(300)	M	∥	10	7
10R(54)′	2 729 129.8	109.849	91.0340	21(160)	M	∥	−19	7
10P(30)″	2 695 149.6	111.234	89.9005	13(100)	M	∥	−8	7
10R(44)	2 651 522.1	113.064	88.4453	44(330)	S	∥	−22	7
10R(50)″	2 638 537.7[d]	113.621	88.0121	29(220)	S	∥	7	7
	2 638 540.7[d]	113.621	88.0122	29(220)	S	∥	7	7
10P(4)‴	2 625 546.4	114.183	87.5788	28(210)	S	∥	42	7
10R(4)	2 574 085.5	116.466	85.8623	39(290)	VS	∥	39	7
10R(18)″		116.7		40(300)	M	∥	−33	7
10R(6)	2 565 990.1	116.833	85.5922	5(40)	M			6
10P(18)″	2 555 898.1	117.294	85.2556	27(200)	W	∥	26	8
9P(22)	2 510 428.7	119.419	83.7389	43(320)	W	∥	39	8
9P(52)	2 473 562.9	121.199	82.5092	27(200)	S	∥	−45	7
10P(24)″	2 460 606.8	121.837	82.0770	27(200)	M	∥	13	8
10P(44)	2 452 677.4	122.231	81.8125	27(200)	VS			6
10SP(29)	2 432 134.3	123.263	81.1273	27(200)	VS	⊥	−12	8
10P(4)″	2 415 908.4	124.090	80.5860	39(290)	M	∥		7
9R(4)		125.7		20(150)	M	∥		7
10SR(11)	2 381 482.4[c]	125.885	79.4377	13(1000)	S	∥	36	7
	2 381 478.9[c]	125.885	79.4376	13(100)	S	∥	36	7
10R(54)″	2 340 717.5	128.077	78.0779	33(250)	S	∥	19	7
9P(36)″	2 225 036.9	134.736	74.2192	27(200)	W			6
10P(06)′	2 221 963.2	134.922	74.1167					5
10P(32)	2 219 596.6	135.066	74.0378	19(140)	W	∥	0	8
10P(6)″	2 174 579.3	137.862	72.5362					5
10R(52)	2 106 238.3	142.335	70.2565	43(320)	S	∥	40	7
9P(50)	2 104 368.9	142.462	70.1942	20(150)	VS	∥	43	7
10P(4)″	2 098 942.5	142.830	70.0132	20(150)	M	∥		7

(Table continued)

Table 4. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Calculated Wavelength (μm)[b]	Calculated Wave Number (cm^{-1})	Pressure [Pa (mTorr)]	Relative Intensity	Relative Polarization	Offset (MHz)	Ref.
10*R*(20)	2 092 854.4	143.246	69.8101	24(180)	S	⊥		5
10*R*(34)′	2 082 274.2	143.974	69.4572	40(300)	VS	⊥	41	7
10*R*(4)	1 989 217.5	150.709	66.3532					5
10*P*(54)	1 980 809.4	151.348	66.0727	11(80)				6
10*HR*(14)′	1 977 072.4	151.635	65.9480	13(100)	M	∥	−30	7
10R(28)	1 955 291.8	153.324	65.2215	28(210)	S	∥	42	7
10*R*(34)″		153.4		29(220)	VS	∥		7
9*R*(46)	1 945 888.1	154.065	64.9078	11(80)	M	∥	−2	7
9*P*(30)	1 920 424.5	156.107	64.0585	20(150)	M	∥	28	7
10*P*(12)	1 907 887.0	157.133	63.6403	24(180)	M	∥	−43	7
10*P*(10)	1 880 947.4	159.384	62.7417	5(40)	W			6
10*R*(36)″	1 868 475.0	160.448	62.3256	33(250)	S	∥	44	7
9P(46)	1 866 375.4	160.628	62.2556	27(200)	VS	∥	−7	7
10*HP*(24)	1 864 680.0	160.774	62.1990	10(75)	W			6
10*SR*(27)	1 860 374.8	161.146	62.0554	37(280)	S	∥	7	7
10*P*(52)	1 860 374.6	161.146	62.0554		W			6
10*HP*(29)	1 858 872.0	161.277	62.0053	7(50)	VS			6
10*P*(52)	1 833 951.7	163.468	61.1740					6
10*R*(20)		165.0		25(190)		∥		New
10*P*(2)	1 811 655.9	165.480	60.4303	23(170)	M	∥	−11	7
10*HP*(25)	1 708 654.6	175.455	56.9946	19(140)	M			8
10*P*(06)‴	1 647 877.4	181.926	54.9673	20(150)	S	⊥		2
9*P*(56)	1 644 081.4	182.346	54.8407	20(150)	S	∥	−32	7
10*R*(50)″	1 635 937.6	183.254	54.5690	29(220)	M	⊥	7	7
9*P*(36)‴	1 619 248.8	185.143	54.0123	13(100)	W			6
10*SP*(29)	1 615 503.5	185.572	53.8874	20(150)	VS	∥	−12	7
10*P*(04)‴		186.1		24(180)	W	⊥	42	7
10*SR*(17)	1 610 436.0	186.156	53.7184	20(150)	VS	∥	19	7
10*HR*(14)″	1 574 927.0	190.353	52.5339	13(100)	M	⊥	−8	7
10*HP*(20)	1 573 986.2	190.467	52.5025	10(75)				6
10*P*(56)–*HP*(23)	1 556 427.9	192.616	51.9168		VVS			6
10*P*(24)‴	1 554 077.8	192.907	51.8385	15(110)	VS	⊥	−32	1, 2, 6
10*SR*(11)	1 510 382.3	198.488	50.3809	11(80)	W	∥		7
10*R*(40)	1 485 618.5	201.796	49.5549	65(490)	VS	∥	−36	7
10*P*(10)	1 450 431.1	206.692	48.3812	40(300)	M	∥	37	7
10*R*(34)‴	1 371 660.8	218.562	45.7537	40(300)	VS	∥	44	7
10*HP*(32)	1 282 805.7	233.701	42.7898	8(60)	S			6
10*R*(08)	1 281 625.8	233.916	42.7504	13(100)	VS			1, 2
10*R*(34)″		234.0						1
10*R*(12)		234.12		35(260)		∥		New
10*SR*(11)		234.36		13(100)		∥		New
10*R*(38)	1 272 681.1	235.559	42.4521	25(190)	VS	∥		5, 7
10*P*(40)	1 241 985.4	241.382	41.4282	7(50)	M			6
10*P*(6)‴		246.5						1
9*R*(10)″	1 203 541.3	249.092	40.1458	20(150)	M	∥	−20	1, 7
10*R*(30)	1 132 510.3	264.715	37.7765	33(250)	S	∥	−10	1, 7
10*R*(20)	1 132 140.6	264.801	37.7641	27(200)	S	∥		1, 2
10*P*(28)		265.0				⊥		1
10*SR*(9)	1 126 495.9	266.128	37.5759	20(150)	VS	⊥	0	7
10*SR*(23)‴		267.4		32(240)	M	∥	47	7
10*P*(18)″		273.0		13(100)	W	∥		1
9*R*(34)	1 055 803.2	283.947	35.2178	13(100)	VS	∥		7
10*HP*(32)	1 042 133.2	287.672	34.7618	8(60)	S			6
10*HP*(29)	1 040 932.6	288.004	34.7218	8(60)	M	∥		6
10*HP*(22)	1 037 179.7	289.046	34.5966	24(180)	M	⊥		8
10*R*(12)	995 077.8	301.275	33.1922	20(150)	S	∥		1, 2

(*Table continued*)

Table 4. Continued

$^{12}C^{16}O_2$ Laser Pump Line[a]	Frequency (MHz)	Calculated Wavelength (μm)[b]	Calculated Wave Number (cm^{-1})	Pressure [Pa (mTorr)]	Relative Intensity	Relative Polarization	Offset (MHz)	Ref.
$9P(20)$	963 731.4	311.075	32.1466					1, 2
$10R(36)''$	960 791.1	312.027	32.0485	37(280)	S	$\perp$	44	7
$9P(46)$	960 791.1	312.027	32.0485	27(200)	VS	$\parallel$	−7	7
$10P(42)$	954 857.6[c]	313.966	31.8506					6
$10P(42)$	954 850.7[c]	313.968	31.8504					6
$10SR(21)$	939 054.3	319.249	31.3235	27(200)	VS	$\parallel$		7
$9R(26)$	916 511.7	327.102	30.5715	20(150)	S	$\parallel$	−13	1, 7
$9P(12)'$	904 899.4	331.299	30.1842	20(150)	S	$\parallel$		2, 6
$9P(30)$		331.5						1
$9P(12)''$	903 889.6	331.669	30.1505	20(150)	S	$\parallel$		1, 2, 6
$10P(24)'''$		336.0						1
$10P(56)-HP(23)$	885 606.8	338.516	29.5407		S			6
$9R(42)$	858 156.2	349.345	28.6250	20(150)	VS	$\perp$		6, 7
$9R(18)$	812 750.0	368.862	27.1104	27(200)	M			3
$10P(18)''$		372.5						1
$10R(12)$	802 492.8	373.576	26.7683					1, 5
$10P(24)'''$	687 957.4	435.772	22.9478					1, 2
$9R(46)$		454.7		33(250)	M	$\parallel$	−2	7
$10P(16)''$	650 207.7	461.072	21.6886					1, 2
$10SR(09)$	645 737.5	464.264	21.5395	19(140)	VS	$\parallel$	0	7
$9P(20)$		483.5						1
$9R(48)$	574 117.3	522.180	19.1505	7(50)	W			6
$10P(42)$	569 599.7[c]	526.321	18.9998					6
$10P(42)$	569 589.7[c]	526.331	18.9995					6
$10P(40)$	568 210.2	527.608	18.9535	7(50)	W			6
$9P(12)'''$	567 925.4	527.873	18.9440					2
$10R(8)$	561 773.0[c]	533.654	18.7387					1, 5
$10R(8)$	561 771.3[c]	533.656	18.7387					1, 5
$9P(08)$		708.3		20(150)	M	$\parallel$		7
$10P(12)$		721.0						1
$10R(38)$	408 346.7	734.162	13.6210					3
$10P(32)$		795.0						1
$10R(24)$		802.4						1
$10P(22)$		1007.0						1

[a] $'$, $''$, and $'''$ indicate different CO_2 laser frequency offsets from line center.
[b] Calculated from $c = 299\,792\,458$ m/s.
[c] Doublets.

$^{14}N_2{}^{16}O$-pumped FIR laser lines.[9] This table also includes the six N_2O-pumped FIR laser lines previously reported.[10] We have omitted a line whose wavelength was not measured but was reported as pumped by the N_2O $10P(26)$ laser line.[10] Tables 4 and 5 present all the known laser lines (sorted by increasing wavelength), which were obtained by pumping hydrazine with a $^{12}C^{16}O_2$ laser and an $^{14}N_2{}^{16}O$ laser, respectively.

Before our research was started,[5–9] 43 laser lines had been reported (3 were reported twice because of errors in the pumping laser lines)[4]; only 2 had wavelengths less than 200 μm (in the range 181.926–195.0 μm), and the others ranged from 250 to 1007.0 μm. We have shown hydrazine to be a good laser medium, providing many FIR laser lines in the short-wavelength region. Among the 134 lines that we discovered in hydrazine pumped with a $^{12}C^{16}O_2$ laser, 82% have wavelengths in the 49.2–200-μm range. In summary, we now have 194 laser lines from hydrazine in the wavelength range 49.2–1007.0 μm, and the frequencies of 150 of these have been measured. Because it is such an efficient and prolific laser medium, hydrazine is the second most important laser molecule for FIR laser emission, after methanol.

5. FUTURE WORK

We plan to study the N_2O-pumped N_2H_4 system further, looking for more FIR lines and frequency measuring as many of the lines as possible. Also, with so much information now available on the N_2H_4 FIR laser lines, the next obvious step is to assign the upper and lower laser levels.

Table 5. Summary of the Hydrazine FIR Laser Lines Pumped by an $^{14}N_2{}^{16}O$ Laser, Sorted by Increasing Wavelength

$^{14}N_2{}^{16}O$ Laser Pump Line[a]	Measured Frequency (MHz)	Calculated Wavelength (μm)[b]	Calculated Wave Number (cm^{-1})	Pressure [Pa (mTorr)]	Relative Intensity	$^{14}N_2{}^{16}O$ Laser Power (W)	Ref.
10P(32)	3 222 036.9	93.044	107.4756	24(180)	S	4.0	9
10R(36)		98.0		35(260)	M	3.2	9
10P(45)	2 823 544.5	106.176	94.1833	23(170)	M	1.8	9
10R(25)	2 823 287.0	106.186	94.1747	19(140)	W	5.0	9
10P(15)‴	2 631 380.7	113.930	87.7734	19(140)	W	5.4	9
10P(26)		114.2		21(160)	M	4.0	9
10P(24)	2 485 511.6	120.616	82.9077	27(200)	M	6.0	9
10P(16)	2 191 609.6[d]	136.791	73.1042	13(100)	M	6.0	9
	2 191 613.7[d]	136.791	73.1044	13(100)	M	6.0	9
10P(30)	1 902 430.3	157.584	63.4582	8(60)	M	4.0	9
10P(11)	1 858 872.0	161.277	62.0053	9(70)	W	6.0	9
10P(34)	1 426 180.2	210.207	47.5723	7(50)	M	3.8	9
10P(7)	1 371 481.5	218.590	45.7477	27(200)	M	5.0	10
10R(4)	1 369 893.3	218.844	45.6947	9(70)	W	2.6	9
10P(15)″	1 288 113.7	232.738	42.9668	7(50)	W	5.8	9
10P(24)		237.0			M		10
10P(29)		241.6		16(120)	W	6.0	9
10R(24)		257.5		15(110)	W	4.2	9
10P(34)	1 041 094.2	287.959	34.7272	13(100)	W	4.4	9
10R(11)	906 899.8	330.568	30.2509	15(110)	W	5.2	10
10R(38)		339.4		19(140)			9
10P(15)′	801 069.7	374.240	26.7208	9(70)	W	5.8	10
10P(28)		492.4		17(130)	W	5.0	10
10P(11)		575.0			M		10

[a] ′, ″, and ‴ indicate different $^{12}N_2{}^{16}O$ laser frequency offsets from line center.
[b] Calculated from $c = 299\ 792\ 458$ m/s.
[c] Doublets.

ACKNOWLEDGMENTS

We are pleased to acknowledge financial support for this research from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazil), the Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), and the National Institute of Standards and Technology.

REFERENCES

1. S. F. Dyubko, V. A. Svich, and L. D. Fesenko, "Stimulated emission of submillimeter lines of hydrazine, excited by a CO_2 laser," J. Appl. Spectrosc. **20**, 545–546 (1974).
2. H. E. Radford, F. R. Petersen, D. A. Jennings, and J. A. Mucha, "Heterodyne measurements of submillimeter laser spectrometer frequencies," IEEE J. Quantum Electron. **QE-13**, 92–94 (1977).
3. M. Inguscio, G. Moruzzi, K. M. Evenson, and D. A. Jennings, "A review of frequency measurements of optically pumped lasers from 0.1 to 8 THz," J. Appl. Phys. **60**, R161–R192 (1986).
4. N. G. Douglas, *Millimeter and Submillimeter Wavelength Lasers* (Springer-Verlag, New York, 1989), p. 223.
5. H. E. Radford, K. M. Evenson, F. Matsushima, L. R. Zink, G. P. Galvão, and T. J. Sears, "Far infrared laser frequencies of CH_3OD and N_2H_4," Int. J. Infrared Millim. Waves **12**, 1161–1166 (1991).
6. E. C. C. Vasconcellos, L. R. Zink, G. P. Galvão, and K. M. Evenson, "New N_2H_4 far infrared laser lines and frequencies," IEEE J. Quantum Electron. **30**, 2401–2406 (1994).
7. E. C. C. Vasconcellos, S. C. Zerbetto, K. M. Evenson, and L. R. Zink, "New far-infrared hydrazine laser lines and their frequencies," J. Opt. Soc. Am. B **12**, 1334–1337 (1995).
8. S. C. Zerbetto, L. R. Zink, K. M. Evenson, and E. C. C. Vasconcellos, "New N_2H_4 far-infrared laser lines and their frequencies," Int. J. Infrared Millim. Waves **17**, 1041–1047 (1996).
9. E. C. C. Vasconcellos, M. Tachikawa, L. R. Zink, and K. M. Evenson, "Far-infrared hydrazine laser pumped by an N_2O laser," Int. J. Infrared Millim. Waves **18**, 2295–2299 (1997).
10. H. Jones, G. Taubmann, and M. Takami, "The optically pumped hydrazine FIR laser: assignments and new laser lines," IEEE J. Quantum Electron. **QE-18**, 1997–1999 (1982).
11. K. M. Evenson, C. Chou, B. W. Bach, and K. G. Bach, "New cw CO_2 laser lines: the 9-μm hot band," IEEE J. Quantum Electron. **30**, 1187–1188 (1994).
12. M. Tachikawa, K. M. Evenson, L. R. Zink, and A. G. Maki, "Frequency measurements of 9- and 10-μm N_2O laser transitions," IEEE J. Quantum Electron. **32**, 1732–1736 (1996).
13. M. Inguscio, F. Strumia, K. M. Evenson, D. A. Jennings, A. Scalabrin, and S. R. Stein, "Far-infrared CH_3F laser," Opt. Lett. **4**, 9–11 (1979).
14. E. C. C. Vasconcellos, S. C. Zerbetto, J. C. Holecek, and K. M. Evenson, "Short-wavelength far-infrared laser cavity yielding new lines in methanol," Opt. Lett. **20**, 1392–1393 (1995).