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Notes and Lines

New Infrared Laser Lines in Argon, Krypton, and Xenon

E. L. BROWN, M. A. GUNDERSEN, AND P. F. WILLIAMS

***Abstract*—Fourteen new infrared laser transitions in Ar, Kr, and Xe ranging from 3.725 to 17.233 μm are reported. All of the Kr laser transitions and all but one of the Ar and Xe transitions have upper levels in the *s* or *d* state: the majority of the transitions satisfy the condition $\Delta K = \Delta J$. Identification of a previously observed, unidentified laser line at 5.804 μm in Ar is given.**

Nobel gas lasers are of interest for many applications because they exhibit long-term frequency stability, a wide range of wavelengths, and useful power levels. In pulsed systems high peak power has been observed over a wide range of wavelengths [1], [2], [6]. Because of the interest in new infrared (IR) lasers and the lack of published data in the IR under these conditions, a survey of Ar, Kr, and Xe was conducted. A 3 m longitudinal discharge laser capable of operation at pressures down to 5 μ and at current densities up to approximately 175 A/cm^2 was used. Nineteen new transitions were observed, ranging in wavelength from 3.631 to 17.233 μ. All but one of the transitions were identified as neutral species, although it had been anticipated that new transitions at high current densities would be ionized species. The strongest transitions were observed in Kr at 4.15 μ and Xe at 7.8 and 8.4 μ.

A longitudinal discharge laser was used for this work [2]. The plasma tube was made from Pyrex tubing with an inside diameter of 19 mm and the electrical discharge was divided into two 1.5 m sections for better stability. Each end of the laser contained an indium cathode [3] and the center electrodes were grounded anodes constructed from molybdenum. The ends of the plasma tube were sealed with KCl Brewster windows which passed radiation with wavelengths from 0.1 to 17 μm, although the optical quality of the windows hindered oscillation at wavelengths below roughly 1 μm. The optical cavity consisted of a 20 m radius mirror and a flat containing a 3 mm diameter pinhole to couple out radiation. Both mirror surfaces were silver overcoated with thorium oxyfluoride. 0.2 μF capacitors were charged to a voltage of 16–20 kV and discharged through the plasma tube with a spark gap. The current rise time was roughly 1 μs, and peak current densities up to 176 A/cm^2 were obtained.

Rough wavelength measurements were made with various filters and more accurate measurements were made using a half meter double spectrometer with 600 grooves/mm gratings blazed at 16 μm. The laser radiation was detected by a HgCdTe detector with sensitivity extending to 18 μm. With this apparatus, measurements accurate to 0.003 μm could be made between 2 and 18 μm.

EXPERIMENTAL RESULTS

Table I gives a listing of the new laser transitions observed in each of the noble gases [7]. The light pulse occurred typically 100 ns after the beginning of the current pulse and had a pulse length of 200–400 ns depending on the pressure and gas used.

In order to make term assignments, a computer program was written to calculate the energy differences between known energy levels [4], [7] satisfying the *jl* coupling selection rules ($\Delta l = +1$ and $\Delta J = 0, \pm 1$). The measured wavelengths were then compared to those calculated. The procedure was followed not only for neutral species but also for the known ionized species. All but one of the observed wavelengths were identified with neutral transitions. No term assignment could be given to the 13.475 μm line observed in Ar, even after including all the know ionized transitions.

TABLE I
INFRARED TRANSITIONS OBSERVED IN Ar, Kr, AND Xe LASERS

	Measured Wavelength (Microns) ± 0.003	Calculated Wavelength 4	Term Assignment	Relative Line Strength^a	Pressure (Microns)
Ar	5.804^b	5.8037	$4d[1\frac{1}{2}]_2-5p[1\frac{1}{2}]_2$	w	20
	6.812	6.8129	$4d[\frac{1}{2}]_1-5p[1\frac{1}{2}]_2$	w	250
	7.956	7.955	$5d[1\frac{1}{2}]_1-6p[1\frac{1}{2}]_1$	m	20
	11.042	11.0415	$7p[\frac{1}{2}]_0-7s[1\frac{1}{2}]_1$	w	20
	13.475			m	250
Kr	8.115	8.1151	$8s[1\frac{1}{2}]_1-7p[2\frac{1}{2}]_2$	w	50
	9.637	9.639	$6d[1\frac{1}{2}]_1-7p[1\frac{1}{2}]_1$	w	50
	10.937	10.9337	$5d[\frac{1}{2}]_1-6p[\frac{1}{2}]_1$	m	50
	17.070	17.0709	$4d'[2\frac{1}{2}]_3-6p[2\frac{1}{2}]_3$	m	50
	17.233	17.2328	$4d'[2\frac{1}{2}]_3-6p[2\frac{1}{2}]_2$	m	50
Xe	3.725	3.7265	$5d'[2\frac{1}{2}]_2-7p[2\frac{1}{2}]_3$	w	150
	7.767	7.7665	$6d[1\frac{1}{2}]_1-7p[1\frac{1}{2}]_1$	s	150
	7.782	7.7813	$5d'[1\frac{1}{2}]_1-8p[1\frac{1}{2}]_1$	s	150
	8.404	8.4042	$6d[1\frac{1}{2}]_1-7p[\frac{1}{2}]_0$	s	150
	11.582	11.5821	$9p[\frac{1}{2}]_0-9s[1\frac{1}{2}]_1$	m	20

[a] Pulse energies for the strong lines were of the order .1-1μJ.

[b] reported in Ref.5.

Term assignments obtained in this manner are given in Table I using Racah *jl* notation with the upper levels given first. The energy levels are denoted by $nl[K]j$ with an unprimed l value indicating a $^2P_{3/2}$ core state and a primed l value indicating a $^2P_{1/2}$ core. Transitions appear to occur in groups sharing initial levels.

A term assignment for the previously observed but unidentified 5.804 μm line in Ar [5] is given in the table. Two d'-p transitions in Kr and two transitions in Xe have been listed in the Table that involve a change in the parent core configuration. Although these transitions are forbidden by selection rules for *jl* coupling, similar transitions have been previously reported [1]. In addition, because the density of states increases for the high lying levels, for an equal distribution of electron energies these levels have a lower probability of attaining a sufficient population to produce an inversion. Therefore, transitions with upper levels above about 8*s*, 7*p*, 6*d* are neglected.

All of the Kr transitions observed and all but one of the Ar and Xe transitions have upper levels in the *s* or *d* state. Previous observations [1] suggest that inversion between the *s*-*p* and *d*-*p* states can be produced by electron impact excitation. When the primary excitation mechanism is due to electron impact with electron energies well above the threshold, excita-

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tion can occur predominately from the ground state p-shell to s and d states that are strongly connected to the ground states by optical transitions. From a calculation of line strengths, it may be shown that the strongest transitions satisfy $\Delta K = \Delta J$ [2]. All of the transitions in Xe, all but one transition in Ar, and half of the transitions in Kr satisfy this condition.

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