

6s. Optical Masers

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6s-1. Introduction. In the short time since the first explicit proposals [1] that stimulated emission be used as an amplifying mechanism, devices employing this principle have become common in the microwave and optical regions of the spectrum. Less than three years passed between the proposal and the observation by Zweiger and Townes [2] of gain ammonia gas at 23.879 kmc. After these initial experiments, it was clear that stimulated emission could be used to build either amplifiers or oscillators. The original work led to the construction of an amplifier using ammonia gas, in which the inverted system was prepared by the electromagnetic separation of the excited ammonia molecules. The device was called a *maser*, which is an acronym for Microwave Amplification by Stimulated Emission of Radiation. In 1960, when Maiman [3] first reported stimulated emission in the optical region of the spectrum, an additional acronym came into use—"laser" for Light Amplification by Stimulated Emission of Radiation. The extension from the microwave region to the optical portion of the spectrum of the use of stimulated emission as an amplifying mechanism followed an explicit proposal to use a 3-level energy system for a maser. In this suggestion, pumping or inversion was to be accomplished by an external energy source and stimulated emission was to occur between two of the three levels. This Bloembergen proposal was first successfully carried out by Scovil, Feher, and Seidel [5].

In the construction of oscillators the active material must be contained in a cavity with means to control the mode of oscillation. At frequencies $< 10^{11}$ Hz, cavities with all dimensions comparable to wavelengths can be built, making mode selection straightforward. This approach is not convenient at optical frequencies. The solution to the problem of control by using a multimode cavity in the form of an interferometer and the natural line width of the transition was suggested by Schawlow and Townes [6]. This suggestion is used in operating lasers. As a consequence of the form of the cavity used, the output of a laser is a beam with a well-defined phase front. The angular divergence of the beam should be diffraction-limited by the cavity aperture. Although clearly predicted, the output radiation of an optical maser in the form of a well-collimated beam of radiation is one of its most striking properties. The isolation of single oscillating modes from lasers is now common practice. Accompanying the appearance of the directional beam, the spectral line width decreases. Within the narrow beam width of the output, the high radiation level occurs. Using Nd^{3+} doped glasses, lasers have been constructed with peak power outputs of $\sim 10^{12}$ watts at $1.06 \mu\text{m}$ for $\sim 3 \times 10^{-12}$ sec [7].

In addition to the requirement of mode selection [30], oscillations can be sustained only if the rate of supplying energy to the mode through emission exceeds the rate of loss of energy from the cavity. This statement can be simply expressed in terms of the absorption coefficient. From thermodynamic considerations of an atom containing only two energy levels, each of statistical weight unity, the probability that a light wave incident on an atom in the ground state will be absorbed is equal to the prob-

ability that the light wave will stimulate the emission of radiation from an atom in the upper state. It should be noted that the radiation produced by the stimulated emission will have the same phase and direction as the original radiation. Light passing through a crystal l cm long, containing N_0 atoms/cm³ all in the ground state, is attenuated by an amount $e^{-\sigma N_0 l}$, where σ is the cross section for absorption (or stimulated emission) at the wavelength of the radiation. On the other hand, if all the atoms were in the upper state, the light would be amplified by $e^{+\sigma N_0 l}$. To sustain oscillations in a cavity the gain must exceed the loss, and thus, with end reflectivities R_1 and R_2 ,

$$e^{2\sigma \Delta n l} \geq \frac{1}{R_1 R_2} \quad (6s-1)$$

where $\sigma \Delta n l$ is the gain/transversal, and Δn is the excess population in the upper level over the lower level. Through the relation between absorption coefficients and line widths, (Δn), the excess population needed to satisfy the above condition, for a gaussian line shape, is

$$\Delta n \geq \frac{4\pi^2}{\sqrt{\pi \ln 2}} \frac{\tau \Delta \nu}{\lambda_1^2} \ln \frac{1}{\sqrt{R_1 R_2}} \quad (6s-2)$$

where λ = wavelength in the medium

τ = radiative lifetime in the upper level

$\Delta \nu$ = full width of the half maximum of the transition

A consideration of Eq. (6s-2) and its implications will indicate some of the properties of a material suitable for a laser. Initially, of course, energy levels connected by a radiative transition must be found in which an inversion of population can be created.

The red fluorescence (6,924 Å) of the Cr³⁺ ion of an Al₂O₃ lattice was the first used to satisfy the conditions of small $\Delta \nu$, high quantum efficiency, reasonable τ , and convenient absorption bands for pumping. Figure 6s-1 gives the energy-level diagram of Cr³⁺ in pink ruby, showing the green and violet absorption bands and the two red fluorescent transitions R_1 { $E \rightarrow 4A_2$ } and R_2 { $2A \rightarrow 4A$ }. One serious drawback of ruby as a laser material is evident in Fig. 6s-1. The R_1 emission line originates in the transition from an excited state to the ground state. Hence, before any optical gain by stimulated emission can occur, the ground state must be depopulated. To depopulate the ground state in ruby, the pumping radiation must have $\sim 10^3$ watts/cm² in the green absorption band.

Optical pumping [3,8] of ruby was first accomplished using millisecond-long pulses from Xe flash lamps. In later work, Hg-Xe vapor lamps have been used to produce CW operation.

The first experimental [9] use of stimulated emission in a gas mixture to observe oscillation was in the He-Ne mixture. Excitation of the neon was achieved through collisions of the second kind between neon and excited atoms of helium.

The long chain of events leading to the eventual development of lasers began with the explicit introduction by Einstein of stimulated emission. This was followed by the theoretical work of Tolman [10], experimental observations by Ladenburg [11], and recognition by Fabrikant [12], that gain was possible. The immediate activity, however, began in 1951 with several groups actively engaged in attempts to produce gain through stimulated emission.

At present, approximately 1,000 different laser wavelengths have been identified. The range of wavelengths extends from 2,358 Å in Ne IV to 372.80 μm in diethylamine. The distribution of the 350 discrete wavelengths from 2,600 Å to 1 μm is such that almost every increment of 100 Å has several laser lines. The coverage is not as dense from 1 to 10 μm; and from 10 to 370 μm only 70 lines in H₂O, D₂O, NH₂, Ne, CN, BrCN, and diethylamine have been observed.

The output of a laser generally consists of more than one axial mode with frequencies separated by $c/2l$. The simultaneous existence of more than one frequency in the output affects the properties of the beam. When a single-frequency axial and transition are emitted from a well-controlled cavity, the amplitude and frequency are stable [13] to one part in 10^9 . Fluctuations or noise occur largely as phase noise. With more than one frequency the output shows random fluctuations due to phase modulation between the separate frequencies. Through various techniques [14] of mode locking it is possible to produce pulses separated by $\sim 10^{-9}$ and 10^{-12} sec long. In Table 6s-1 is a list of the wavelengths at which laser oscillation has been reported, together with material in which it was observed. For the purpose of this handbook it is not reasonable to discuss each separately. Only the commonly used lasers are treated below.

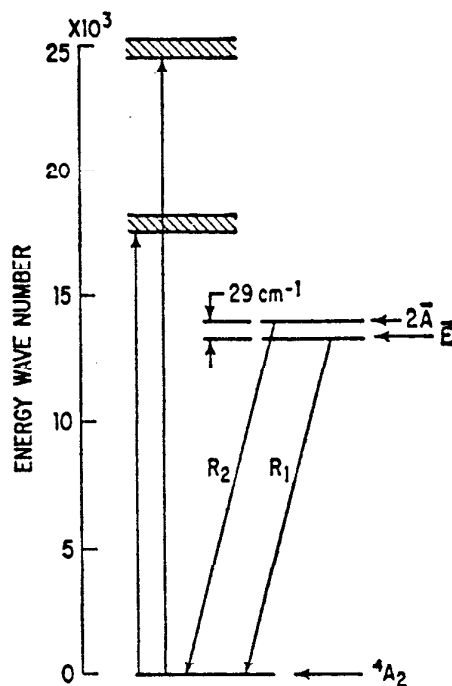


FIG. 6s-1. Energy level Cr^{3+} in Al_2O_3 showing absorption bands and the R_1R_2 emission lines.

In its simplest form a laser consists of a gain medium, a feedback mechanism, a source of input energy, a method of coupling between the input energy and the actual gain medium, and a method of extracting power. The forms of input energy are:

1. Optical energy from gas discharge or incandescent sources (pump lamps). The first pump lamps used were the Xe flash lamps. Later lamps included mercury vapor, tungsten, ribbons, the sun, other lasers, light-emitting diodes, and shock waves.
2. Electric discharges in the gaseous material itself.
3. Thermal excitation of one species followed by excitation of the actual gain material.
4. Direct electrical injection of carriers in semiconductor junctions.
5. Electron-beam excitation of solids. In these cases the incident electron-beam energy varies from $\sim 50,000 \rightarrow 300,000$ electron volts.
6. Chemical dissociation into excited states.
7. Exothermic chemical reaction producing molecules in excited states.
8. Thermodynamic processes—e.g., rapid expansion of gases.

TABLE 6s-1. OBSERVED LASER OSCILLATIONS*

Wave-length, μm	Material	Reference	Wave-length, μm	Material	Reference
0.23580	Ne IV	42	0.338554	O IV	42
0.247350	Ne	42	0.339286	Ne II	42
0.247718	Xe	42	0.339287	Cl III	43
0.262490	Ar IV	42	0.339340	Ne II	42
0.263270	Cl	43	0.339345	Cl III	43
0.264041	Kr	42	0.345423	Xe III	42
0.266450	Kr II	42	0.347870	N IV	42
0.267798	Ne III	42	0.348296	Xe	42
0.267868	Ne III	42	0.348302	N IV	42
0.269182	Xe	42	0.350742	Kr III	42
0.274151	Kr	42	0.351113	Ar III	42
0.275391	Ar III	42	0.351415	Ar III	42
0.275959	F III	43	0.353003	Cl III	43
0.27775	Ne III	42	0.356069	Cl III	43
0.282608	F IV	43	0.356420	Kr III	42
0.28688	Ne	42	0.35769	Ar II	42
0.288424	Ar III	42	0.363786	Cl III	43
0.291292	Ar IV	42	0.364546	Cl III	43
0.292624	Ar IV	42	0.366920	Cl III	43
0.29837	Xe III	42	0.363786	Ar III	42
0.298386	O III	42	0.364546	Xe	42
0.300264	Ar	42	0.366920	Xe	42
0.3024	Ar III	42	0.37052	Ar	42
0.304715	O III	42	0.372046	Cl III	43
0.304974	Kr	42	0.374573	Xe III	42
0.30548	Ar III	42	0.374878	Cl III	43
0.306346	O IV	42	0.374949	OH	42
0.307979	Xe	42	0.375468	O III	42
0.312156	F III	43	0.3757	ZnO	50
0.312443	Kr III	42	0.375986	O III	42
0.3125	Gd ⁺⁺ (glass)	42	0.378099	Xe III	42
0.217418	F III	43	0.378528	Ar III	42
0.319143	Cl III	43	0.380327	Xe	42
0.320274	F II	43	0.385826	Ar III	42
0.323943	Kr III	43	0.397293	Xe	42
0.324694	Xe III	43	0.399499	N II	43
0.325	ZnS	49	0.402478	F II	43
0.330592	Xe	42	0.406048	Xe III	42
0.331984	Ne II	42	0.406736	Kr III	42
0.332379	Ne II	42	0.409729	N III	42
0.332437	Ne	42	0.410326	N III	42
0.33275	Ne II	42	0.413128	Kr III	42
0.332902	Ne II	42	0.41325	Cl II	43
0.333082	Xe	42	0.414000	Ar III	42
0.333107	Ne III	42	0.415445	Kr III	42
0.33614	Ar III	42	0.417181	Kr III	42
0.334478	Ar III	42	0.418292	Ar	42
0.334550	Ne II	42	0.421405	Xe III	42
0.334776	P IV	43	0.422225	P III	43
0.335004	Xe	42	0.422651	Kr III	42
0.335852	Ar III	42	0.424026	Xe III	42
0.336732	N III	42	0.427460	Xe III	42
0.33750	Kr III	42	0.428592	Xe III	42
0.337833	Ne III	42	0.430577	Xe III	42
0.338134	O IV	42	0.4318	Kr II	42

* The references for this table have been selected, not for historical purposes, but on the grounds of availability in modest libraries and to lead the user into the appropriate literature.

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Refer-ence	Wave-length, μm	Material	Refer-ence
0.434738	O II	42	0.491	CdS	27
0.435126	O KK	42	0.491766	Cl II	43
0.437073	Ar II	42	0.492404	Zn II	59
0.4387	Kr II	42	0.495410	Xe III	42
0.441493	O II	42	0.496500	Xe II	42
0.44156	Cd	59	0.496509	Ar II	42
0.441697	O II	42	0.4986	I II	42
0.443422	Xe III	42	0.499255	Ar	42
0.444328	Kr III	42	0.500772	Xe	42
0.4482	Ar II	42	0.50164	Kr II	42
0.451045	N III	42	0.501717	Ar II	42
0.451441	N III	42	0.5022	Kr II	42
0.454504	Ar II	42	0.504489	Xe II	42
0.455259	F	43	0.505463	Br II	64
0.456784	F	43	0.507830	Cl II	43
0.457720	Kr II	42	0.5097	Se II	65
0.457936	Ar II	42	0.51031	Cl II	44
0.4583	Kr II	42	0.5126	Kr II	42
0.460302	Xe II	42	0.513175	Ge II	59
0.460552	O	42	0.51418	Ar II	42
0.460957	Ar II	42	0.514533	Ar II	42
0.46152	Kr II	42	0.515904	Xe	42
0.461917	Kr II	42	0.517865	Ge II	59
0.463031	N II	42	0.518238	Br II	64
0.463392	Kr II	42	0.5185	Br II	65
0.464740	C III	47	0.520832	Kr II	42
0.464908	O II	42	0.5216	I II	42
0.465011	C III	47	0.521790	Cl II	43
0.465016	Kr II	42	0.522130	Cl II	43
0.465795	Ar II	42	0.5228	Se II	66
0.467373	Xe III	42	0.523826	Br II	64
0.468045	Kr II	42	0.523889	Xe III	42
0.46805	In II	59	0.526017	Xe II	42
0.468357	Xe III	42	0.52615	Xe II	42
0.4695	Kr II	42	0.5287	Ar II	42
0.47231	Xe III	42	0.530868	Kr II	42
0.472689	Ar II	42	0.5314	Xe II	42
0.47404	Cl II	43	0.53207	S II	59
0.474266	Br II	64	0.533203	Br II	64
0.474892	Xe	48	0.5334	Br II	65
0.476244	Kr II	42	0.533749	Cd II	60
0.476488	Ar II	42	0.53410	Mn I	61
0.476571	Kr II	42	0.53457	S II	59
0.476874	Cl II	42	0.535289	Xe	42
0.478134	Cl II	42	0.53721	Pb II	59
0.4797	Hg III	42	0.537804	Cd II	60
0.482518	Kr II	42	0.539215	Cl II	43
0.484666	Kr II	42	0.539459	Xe	42
0.4862	Xe II	42	0.54009	Xe III	55
0.486948	Xe III	42	0.5407	I II	42
0.487986	Ar II	42	0.5419	I	42
0.4887	Xe II	42	0.541916	Xe II	42
0.488906	Ar II	42	0.54204	Mn I	61
0.489688	Cl II	43	0.54287	S II	59
0.490473	Cl II	43	0.54328	S II	59

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Reference	Wave-length, μm	Material	Reference
0.54538	S II	59	0.6130	Eu ⁺⁺ (chelate)	69
0.54703	Mn I	61	0.6150	Hg II	42
0.54736	S II	59	0.616574	P II	43
0.5498	As II	65	0.616880	Kr II	48
0.55022	Ar III	42	0.6171	As II	65
0.55164	Mn I	61	0.627090	Xe II	42
0.552439	Xe III	52	0.6293	He-Ne	95
0.55375	Mn I	61	0.6328	He-Ne	95
0.5559	As II	65	0.634724	F	43
0.55906	CO	62	0.637148	F	43
0.559237	O III	42	0.6401	He-Ne	95
0.55934	CO	62	0.65530	Sn II	59
0.55960	CO	62	0.64710	Kr II	42, 48
0.55983	CO	62	0.652865	Xe II	52
0.56004	CO	62	0.65700	Kr II	42, 48
0.56025	CO	62	0.6585	I II	42
0.56038	CO	62	0.65955	CO	62
0.5625	I II	42	0.65995	CO	62
0.56400	S II	59	0.66031	CO	62
0.56470	S II	59	0.66064	CO	62
0.5652	As II	65	0.66091	CO	62
0.5650	Xe II	42	0.66115	CO	62
0.566662	N II	42	0.66135	CO	62
0.567803	N II	42	0.667193	P	43
0.5678	Hg II	42	0.672138	O II	42
0.5678	I II	42	0.676457	Kr II	42, 48
0.567953	N II	42	0.68400	Sn II	59
0.568192	Kr II	42	0.685	Cd Se	27
0.5727	Xe II	42	0.687096	Kr II	42, 48
0.5751	Xe II	42	0.690	CdSSe	27
0.5753	Kr II	42	0.6904	I II	42
0.5760	I II	42	0.6943	Cr ⁺⁺ (Al ₂ O ₃)	3, 8, 72
0.57987	Sn II	59	0.6969	Sm ⁺⁺ (SrF ₂)	74
0.5939	He-Ne	95	0.7010	Cr ⁺⁺ (Al ₂ O ₃)	71
0.594	GaSe	27	0.7032	I II	42
0.595573	Xe	42	0.7040	Cr ⁺⁺ (Al ₂ O ₃)	71
0.597112	Xe II	42	0.7083	Sm ⁺⁺ (CaF ₂)	74
0.5985	Pr ⁺⁺ (LaF ₃)	91	0.7346	Hg II	42
0.602427	P II	43	0.74783	Zn II	59
0.603419	P II	43	0.75875	Zn II	59
0.604312	P II	59	0.76118	Zn II	59
0.6046	He-Ne	95	0.775786	Zn II	59
0.60629	CO	62	0.7828	Xe II	42
0.60657	CO	62	0.784563	P II	59
0.60682	CO	62	0.786	CdTe	27
0.60705	CO	62	0.7989	Xe II	42
0.60725	CO	62	0.79930	Kr II	42
0.60742	CO	62	0.8250	I II	42
0.608804	P II	43	0.8330	Xe II	42
0.6094	Xe II	42	0.834961	H ₂	75
0.609474	Cr ⁺⁺	43	0.84	Ga AsP	27
0.61028	Zn II	59	0.8408	Xe	42
0.6113	Eu ⁺⁺ (Y ₂ O ₃)	68	0.8443	Xe II	42
0.6118	He-Ne	95	0.8446	O I	42
0.6127	I II	42	0.8446	Ne-O ₂	41

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Reference	Wave-length, μm	Material	Reference
0.84463	Br I	41	1.0461	N ₂	66
0.84464	Br I	41	1.0468	Pr ³⁺ (CaWO ₄)	78
0.84467	Br I	41	1.0472	N ₂	66
0.84468	Br I	41	1.0480	N ₂	66
0.845	Ga As	27, 70	1.0491	N ₂	66
0.8547	Hg II	42	1.0495	N ₂	66
0.8569	Xe	42	1.0505	N ₂	66
0.8582	Xe II	42	1.057	Nd ³⁺ (borate glass)	26
0.8589	Kr II	42	1.0574	Nd ³⁺ (SrWO ₄)	73
0.9628	Hg II	42	1.0576	Nd ³⁺ (CaWO ₄)	73
0.8677	Hg	42	1.0576	Nd ³⁺ (SrMoO ₄)	73
0.8684	N ₂	66	1.0586	Hg II	42
0.8691	N ₂	66	1.0586	Nd ³⁺ (PbMoO ₄)	73
0.8698	N ₂	66	1.050	Nd ³⁺ (SrMoO ₄)	73
0.8704	N ₂	66	1.06	Nd ³⁺ (CaWO ₄)	73
0.87099	N ₂	66	1.06	Nd ³⁺ (SeOCl ₂)	77
0.8714	Xe II	42	1.06	Nd ³⁺ (silicate glass)	26
0.8780	Ar II	42	1.06	Nd ³⁺ (YAG)	76
0.8800	I II	42	1.060	Nd ³⁺ (BaF ₂)	73
0.8844	N ₂	66	1.0607	Nd ³⁺ (SrWO ₄)	73
0.8847	N ₂	66	1.061	Nd ³⁺ (CaMoO ₄)	73
0.8852	N ₂	66	1.061	Nd ³⁺ (barium crown glass)	26
0.8856	N ₂	66	1.0611	Nd ³⁺ (SrMoO ₄)	73
0.8862	N ₂	66	1.0618	SI	41
0.8871	N ₂	66	1.0621	He-Ne	95
0.887625	H ₂	75	1.0623	Nd ³⁺ (Gd ₂ Ca ₂ O ₁₂)	76
0.8879	N ₂	66	1.0627	Nd ³⁺ (SrMoO ₄)	73
0.8886	N ₂	66	1.0631	Nd ³⁺ (LaF ₃)	73
0.8892	N ₂	66	1.0633	Nd ³⁺ (CaWO ₄)	73
0.8898	N ₂	66	1.0633	Nd ³⁺ (Y ₂ Ca ₂ O ₁₂)	76
0.889884	H ₂	75	1.0634	Xe II	
0.8909	N ₂	66	1.0638	Nd ³⁺ (CeF ₃)	94
0.9003	Xe II	42	1.0640	Nd ³⁺ (SrMoO ₄)	73
0.907	InP	27	1.0641	Nd ³⁺ (CaWO ₄)	73
0.9145	Nd ³⁺ (CaWO ₄)	73	1.0650	Nd ³⁺ (CaWO ₄)	73
0.9180	Nd ³⁺ (glass)	26	1.0652	Nd ³⁺ (SrMoO ₄)	73
0.9265	Xe II	42	1.066	Nd ³⁺ (CaWO ₄)	73
0.9287	Xe II	42	1.067	Nd ³⁺ (CaMoO ₄)	73
0.9396	Hg II	42	1.0689	C I	41
0.9451	Cl I	92	1.073	Nd ³⁺ (Y ₂ O ₃)	78
0.9697	Xe II	42	1.0741	Nd ³⁺ (Gd ₂ O ₃)	78
0.98	I	45	1.078	Nd ³⁺ (Y ₂ O ₃)	78
1.01	I	45	1.0789	Nd ³⁺ (Gd ₂ O ₃)	78
1.015	Yb ³⁺ (silicate glass)	26	1.0798	He-Ne	95
1.0295	Ne I	87	1.0844	He-Ne	95
1.0296	Yb ³⁺ (YAG)	88	1.0923	Ar II	56
1.03	I	45	1.0935	Ar	56
1.037	Nd ³⁺ (SrF ₂)	73	1.0950	Xe	42
1.0399	Nd ³⁺ (LaF ₃)	78	1.1181	Hg II	42
1.04	I	45	1.1143	He-Ne	95
1.04	Pr ³⁺ (Ca(NbO ₃) ₂)	93	1.116	Tm ³⁺ (CaF ₂)	73
1.0437	Nd ³⁺ (SrF ₂)	73	1.116214	H ₂	73
1.0449	N ₂	66	1.1177	He-Ne	95
1.0455	SI	41	1.1180	He-Ne	95
1.0457	Nd ³⁺ (CaF ₂)	41	1.1181	Hg II	42

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Reference	Wave-length, μm	Material	Reference
1.1222	H ₂	75	1.5550	Hg II	42
1.1390	He-Ne	95	1.60	InPAs	27
1.1409	He-Ne	95	1.61	Er ³⁺ (Ca(NbO ₃) ₂)	78
1.1523	He-Ne	95	1.612	Er ³⁺ (CaWO ₄)	78
1.1525	He-Ne	95	1.618	Ar I	53
1.1601	He-Ne	95	1.622	Ni ²⁺	90
1.1614	He-Ne	95	1.6452	Er ³⁺ (YAG)	73
1.1617	He-Ne	95	1.6602	Er ³⁺ (YAG)	73
1.1767	He-Ne	95	1.690	Kr I	53
1.1770	He-Ne	95	1.6918	Hg I	18
1.1788	Ne I	87	1.6921	Hg I	18
1.1790	Ne I	87	1.694	Ar I	53
1.1985	He-Ne	95	1.694	Kr I	53
1.1988	He-Ne	95	1.6942	Hg I	18
1.2066	He-Ne	95	1.7073	Hg I	18
1.2069	He-Ne	95	1.7110	Hg I	18
1.2303	N ₂	66	1.7162	Ne I	87
1.2312	N ₂	66	1.750	Co ²⁺	78
1.2319	N ₂	66	1.77	InGaAs	27
1.2334	N ₂	66	1.784	Kr	53
1.2347	N ₂	66	1.793	Ar	53
1.2459	Ne I	87	1.803	Co ²⁺	78
1.2545	Hg	42	1.8130	Hg I	53
1.2689	He-Ne	95	1.819	Kr	53
1.2887	He-Ne	95	1.8210	Ne I	87
1.28961	Mn I	61	1.8281	He-Ne	95
1.2912	He-Ne	95	1.8287	He-Ne	95
1.2981	Hg	42	1.8309	He-Ne	95
1.30578	H ₂	75	1.8408	He-Ne	95
1.31623	H ₂	75	1.8596	He-Ne	95
1.32932	Mn I	61	1.8602	He-Ne	95
1.33174	Mn I	61	1.8751	H I	75
1.3372	Nd ³⁺ (CaWO ₄)	78	1.880	Tm ³⁺ (YAG)	88
1.345	Nd ³⁺ (CaWO ₄)	78	1.884	Tm ³⁺ (YAG)	88
1.3472	Ar I	56	1.91	Tm ³⁺ (Ca(NbO ₃) ₂)	78
1.3585	N I	41	1.911	Tm ³⁺ (CaWO ₄)	73
1.36246	Mn I	61	1.916	Tm ³⁺ (CaWO ₄)	73
1.3655	Hg I	42	1.921	Kr I	53
1.37	Nd ³⁺ (glass)	26	1.934	Tm ³⁺ (Er ₂ O ₃)	78
1.3859	Cl I	43	1.9574	Ne I	87
1.38641	Mn I	61	1.9577	Ne I	87
1.387	Nd ³⁺ (CaWO ₄)	78	1.972	Tm ³⁺ (SrF ₂)	73
1.3891	Cl I	43	1.9755	Cl I	86
1.39956	Mn I	61	1.992	Co ²⁺	78
1.401	Nd ³⁺ (borate glass)	26	2.014	Tm ³⁺ (YAG)	88
1.4539	C I	41	2.0199	Cl I	86
1.4542	II	46	2.0267	Xe I	53
1.4544	N I	41	2.0350	Ne I	87
1.48	Er ³⁺ (YAl ₃ O ₇)	78	2.0354	Ne I	87
1.5	Er ³⁺ (YAl ₃ O ₇)	78	2.046	HO ²⁺ (CaWO ₄)	73
1.51	GaSb	27	2.047	HO ²⁺ (Ca(NbO ₃) ₂)	78
1.5231	He-Ne	95	2.053	Co ²⁺	78
1.5235	He-Ne	95	2.059	HO ²⁺ (CaWO ₄)	73
1.5295	Hg I	57	2.0616	Ar I	53
1.5426	Er ³⁺ (glass, Er ³⁺ - Yb ³⁺)	89	2.0650	C I	82

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Reference	Wave-length, μm	Material	Reference
2.0650	C I	82	2.967	Ne I	53
2.07	InGaAs	40	2.9788	Ar I	53
2.092	Ho ³⁺ (CaF ₂)	73	2.9810	Ne I	53
2.092	Ho ³⁺ (YAG)	78	2.9845	Kr I	53
2.098	Ho ³⁺ (YAG)	78	2.9878	Kr I	53
2.10119	Ne I	53	3.0268	Ne I	53
2.1041	He-Ne	95	3.0278	Ne I	53
2.116	Kr I	53	3.0453	Ar I	53
2.123	Ho ³⁺ (YAG)	78	3.0536	Kr	53
2.1339	Ar I	53	3.0672	Kr I	53
2.1708	He-Ne	95	3.0996	Ar I	53
2.189	Kr I	53	3.1	In As	27
2.2045	Ar I	53	3.0078	Xe I	53
2.2	U ³⁺	73	3.1333	Ar I	53
2.2845	Br I	85	3.1346	Ar I	53
2.3139	Ar I	53	3.1515	Kr I	53
2.3200	Xe I	53	3.20	Ce	54
2.3260	Ne I	53	3.236	I I	84
2.3511	Br I	85	3.24804	N ₂	17
2.36	Dy ³⁺ (CaF ₂)	78	3.2739	Xe I	53
2.3951	Ne I	53	3.29522	N ₂	67
2.398	He-Ne	95	3.30756	N ₂	67
2.3973	Ar I	53	3.31240	N ₂	67
2.4466	Cl I	86	3.31616	N ₂	67
2.5	U ³⁺	78	3.3179		53
2.5014	Ar I	53	3.3182	Ne I	53
2.523	Kr I	53	3.31892	N ₂	67
2.5400	Ne I	53	3.3342	Ne I	53
2.5421	Ar I	53	3.3362	Ne I	53
2.5404	Ar I	41	3.3409	Kr I	53
2.5512	Ar I	41	3.3419	Kr I	53
2.5524	Ne I	53	3.3676	Xe I	53
2.5364	Ar I	41	3.3813	Ne I	53
2.5668	Ar I	41	3.3849	Ne I	53
2.5987	I I	84	3.39	He-Ne	95
2.6267	Kr I	53	3.3912	Ne I	53
2.6276	Xe I	53	3.3922	Ne I	53
2.6288	Kr I	53	3.4060	C I	82
2.6518	Xe I	53	3.431	I I	84
2.660	Xe I	53	3.4345	Xe I	53
2.6843	Ar I	53	3.440	Xe I	53
2.7356	Ar I	53	3.4481	Ne I	53
2.7571	I I	84	3.4487		53
2.7581	Ne I	53	3.45212	N ₂	67
2.784	Ne I	53	3.45852	N ₂	67
2.8202	Ar I	53	3.45377	N ₂	67
2.8238	Ar I	53	3.4680	Kr I	53
2.8375	Br I	85	3.46804	N ₂	67
2.8618	Kr I	53	3.47127	N ₂	67
2.864	Ne I	53	3.4883	Kr I	53
2.8663	Ar I	53	3.4895	Kr I	53
2.8783	Ar I	53	3.5080	Xe I	53
2.8843	Ar I	53	3.5160	C I	82
2.9272	Ar I	53	3.5845	Ne I	53
2.9496	Ne I	53	3.6219	Xe I	53

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Refer-ence	Wave-length, μm	Material	Refer-ence
3.6518	Xe I	53	5.27380	CO	63
3.6798	Xe I	53	5.28465	CO	63
3.6859	Xe I	53	5.29570	CO	63
3.700	HCl I	83	5.3000	Kr I	53
3.734	HCl I	83	5.3919	Kr I	53
3.7746	Ne I	53	5.30695	CO	63
3.808	HCl	83	5.31820	CO	63
3.810	HCl	83	5.32415	CO	63
3.840	HCl	83	5.33490	CO	63
3.869	Xe I	53	5.34590	CO	63
3.894	Xe I	53	5.35695	CO	63
3.93	Hg I	58	5.36820	CO	63
3.9817	Ne I	53, 41	5.37950	CO	63
3.9966	Xe I	53	5.54041		53
4.14	HgCdTe	27	5.4048	Ne I	53
4.160	Xe I	53	5.40801	CO	63
4.28	PbS	80	5.41981	CO	63
4.3748	Kr I	53	5.42682	CO	63
4.602	Xe I	53	5.42991	CO	63
4.7330	Ar I	53	5.44247	CO	63
4.8773	Kr I	53	5.4680	Ar I	53
4.8832	Kr I	53	5.4770	Ar I	53
4.9160	Ar I	53	5.5700	Kr I	53
4.9213	Ar I	53	5.5754	Xe I	53
5.03755	CO	63	5.5863	Kr I	53
5.04750	CO	63	5.5970	C I	82
5.05755	CO	63	5.6306	Kr I	53
5.06773	CO	63	5.662	Ne I	53
5.07807	CO	63	5.8477	Ar I	53
5.08845	CO	63	5.98	Hg I	58
5.09905	CO	63	5.8666	Ar I	53
5.10410	CO	63	5.9550	NO	81
5.10985	CO	63	5.9639	NO	81
5.11418	CO	63	5.9750	NO	81
5.1216	Ar I	53	6.0008	NO	81
5.1218	Ar I	53	6.0266	NO	81
5.12445	CO	63	6.0327	NO	81
5.13485	CO	63	6.0386	NO	81
5.14530	CO	63	6.0403	NO	81
5.15595	CO	63	6.050	Ar I	53
5.16666	CO	63	6.0629	NO	81
5.17220	CO	63	6.0885	NO	81
5.17765	CO	63	6.0934	NO	81
5.18250	CO	63	6.1417	NO	81
5.18865	CO	63	6.1545	NO	81
5.19290	CO	63	6.1972	NO	81
5.20	InSb	27	6.2752	NO	81
5.20345	CO	63	6.49	Hg I	58
5.21410	CO	63	6.665	PbTe	80
5.22498	CO	63	6.9429	Ar I	41
5.23600	CO	63	6.9448	Ar I	41
5.24195	CO	63	7.0581	Kr I	41
5.24710	CO	63	7.18	Cs	54
5.25250	CO	63	7.2150	Ar I	53
5.26310	CO	63	7.314	Xe I	51

TABLE 6s-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Refer-ence	Wave-length, μm	Material	Refer-ence
7.33	Ne I	41	10.8416	N ₂ O	33
7.4221	Ne I	41	10.8523	N ₂ O	33
7.4237	Ne I	41	10.8628	N ₂ O	33
7.4799	Ne I	41	10.8736	N ₂ O	33
7.4994	Ne I	41	10.8843	N ₂ O	33
7.6163	Ne I	41	10.8951	N ₂ O	33
7.6461	Ne I	41	10.9061	N ₂ O	33
7.6510	Ne I	41	10.9170	N ₂ O	33
7.6925	Ne I	41	10.9280	N ₂ O	33
7.7015	Ne I	41	10.9390	N ₂ O	33
7.7407	Ne I	41	10.9510	N ₂ O	33
7.7655	Ne I	41	10.9612	N ₂ O	33
7.78	Ne I	41	10.9724	N ₂ O	33
7.8063	Ar I	41	10.98	Ne	33, 53
7.8368	Ne I	41	10.981	Ne I	33
8.0088	Ne I	41	10.9838	N ₂ O	33
8.0621	Ne I	41	10.9951	N ₂ O	33
8.1838 ²	N ₂	67	11.0067	N ₂ O	33
8.337		53	11.0184	N ₂ O	33
8.21106	N ₂	67	11.0296	N ₂ O	33
8.57	PbSe	27	11.0416	N ₂ O	33
8.83370	Ne I	41	11.29	Xe I	53
8.8413	Ne I	41	11.4823	N ₂ -Cs ₂	36
9.004	Xe I	51	11.4893	N ₂ -Cs ₂	36
9.0896	Ne I	41	11.5031	N ₂ -Cs ₂	36
9.5691	CO ₂	32	11.5099	N ₂ -Cs ₂	36
9.5862	CO ₂	32	11.5166	N ₂ -Cs ₂	36
9.6063	CO ₂	32	11.5237	N ₂ -Cs ₂	36
9.6211	CO ₂	32	11.5307	N ₂ -Cs ₂	36
9.6391	CO ₂	32	11.5376	N ₂ -Cs ₂	36
9.657	CO ₂	32	11.5446	N ₂ -Cs ₂	36
9.6762	CO ₂	32	11.5962	N ₂ -Cs ₂	36
9.702	Xe I	51	11.861	Ne I	41
10.063	Ne I	41	11.902	Ne I	41
10.5135	CO ₂	32	12.141	Ar I	41
10.5326	CO ₂	32	12.266	Xe I	41
10.5518	CO ₂	32	12.835	Ne I	41
10.5713	CO ₂	32	12.972	Xe I	41
10.5912	CO ₂	32	13.739	Ne I	41
10.6118	CO ₂	32	13.759	Ne I	41
10.6324	CO ₂	32	14.93	Ne	53
10.6534	CO ₂	32	15.037	Ar I	41
10.6748	CO ₂	32	16.56	PbSnTe	27
10.6965	CO ₂	32	16.638	Ne I	41
10.7194	CO ₂	32	16.668	Ne I	41
10.7415	CO ₂	32	16.893	Ne I	41
10.7698	N ₂ O	33	16.931	H ₂ O	37
10.7748	CO ₂	32	16.947	Ne I	41
10.7799	N ₂ O	33	17.158	Ne I	41
10.7880	CO ₂	33	17.189	Ne I	41
10.7901	N ₂ O	33	17.802	Ne I	41
10.8005	N ₂ O	33	17.837		53
10.8107	N ₂ O	33	17.841	Ne I	41
10.8212	N ₂ O	33	17.888	Ne I	41
10.8312	N ₂ O	33	18.396	Ne I	41

TABLE 6S-1. OBSERVED LASER OSCILLATIONS (Continued)

Wave-length, μm	Material	Refer-ence	Wave-length, μm	Material	Refer-ence
18.506	Xe I	53	55.077	H ₂ O	37
19.472		53	55.68	Ne I	41
20.480	Ne I	41	56.845	D ₂ O	35
21.471	NH ₃	38	57.355	Ne I	41
21.752	Ne I	41	57.660	H ₂ O	37
22.542	NH ₃	38	67.177	H ₂ O	37
22.563	NH ₃	38	68.329	Ne I	41
22.675	NH ₃	38	71.965	D ₂ O	35
22.836	Ne I	41	72.15	Ne I	41
23.365	H ₂ O	37	72.429	D ₂ O	35
24.918	NH ₃	M38	72.747	D ₂ O	35
25.423	Ne I	41	73.337	D ₂ O	35
26.282	NH ₃	38	73.402	H ₂ O	37
26.666	H ₂ O	37	74.545	D ₂ O	35
26.944	Ar I	53	70.305	D ₂ O	35
27.974	H ₂ O	37	78.455	H ₂ O	37
28.053	Ne I	41	79.106	H ₂ O	37
28.054	H ₂ O	37	84.111	D ₂ O	35
28.273	H ₂ O	37	84.291	D ₂ O	35
28.356	H ₂ O	37	84.047	Ne I	41
31.55		53	86.9	Ne I	41
31.028	Ne I	41	88.40	Ne I	41
31.951	NH ₃	38	89.775	H ₂ O	37
32.02		53	89.93	Ne I	41
32.52		53	93.02	Ne I	41
32.929	H ₂ O	37	106.02	Ne I	41
33.033	H ₂ O	37	107.71	D ₂ O	36, 35
33.896	D ₂ O	35	115.42	H ₂ O	37
34.679	Ne I	41	118.65	H ₂ O	37
35.000	H ₂ O	37	120.08	H ₂ O	37
35.090	D ₂ O	35	124.4	Ne I	41
35.602	Ne I	41	126.1	Ne I	41
35.841	H ₂ O	37	126.24	Diethylamine	40
36.319	D ₂ O	35	128.75	Diethylamine	40
36.524	D ₂ O	35	130.95	Diethylamine	40
36.619	H ₂ O	37	132.8	Ne I	41
37.231	Ne I	41	135.03	Diethylamine	40
37.791	D ₂ O	35	171.6	D ₂ O	36
37.859	H ₂ O	37	181.90	Deuterium and BrCN	40
38.094	H ₂ O	37	190.08	Deuterium and BrCN	40
39.096	H ₂ O	37	194.83	Deuterium and BrCN	40
40.629	H ₂ O	37	201.19	Diethylamine	40
40.994	D ₂ O	35	204.53	Deuterium and BrCN	40
41.741	Ne I	41	211.14	Diethylamine	40
45.523	H ₂ O	37	223.25	Diethylamine	40
47.251	H ₂ O	37	309.94	Diethylamine	40
47.469	H ₂ O	37	311.08	Diethylamine	40
47.693	H ₂ O	37	311.3	CN	39
48.677	H ₂ O	37	336.7	CN	39
50.70	Ne I	41	336.83	Diethylamine	40
52.39	Ne I	41	372.80	Diethylamine	40
53.486	Ne I	41			
53.906	H ₂ O	37			
54.019	Ne I	41			
54.117	Ne I	41			

Although the feedback mechanism is reflection, the metallic mirrors used in the first lasers have been replaced by multilayer dielectrics with the reflectivity maximum matched to the wavelength of interest. Another device commonly used for reflectors is the multiple reflections from an etalon of transparent plates.

6s-2. Noble Gas Lasers. One important class of lasers consists of the electrically excited noble gas lasers, and of these the most common is the He-Ne. In the He-Ne

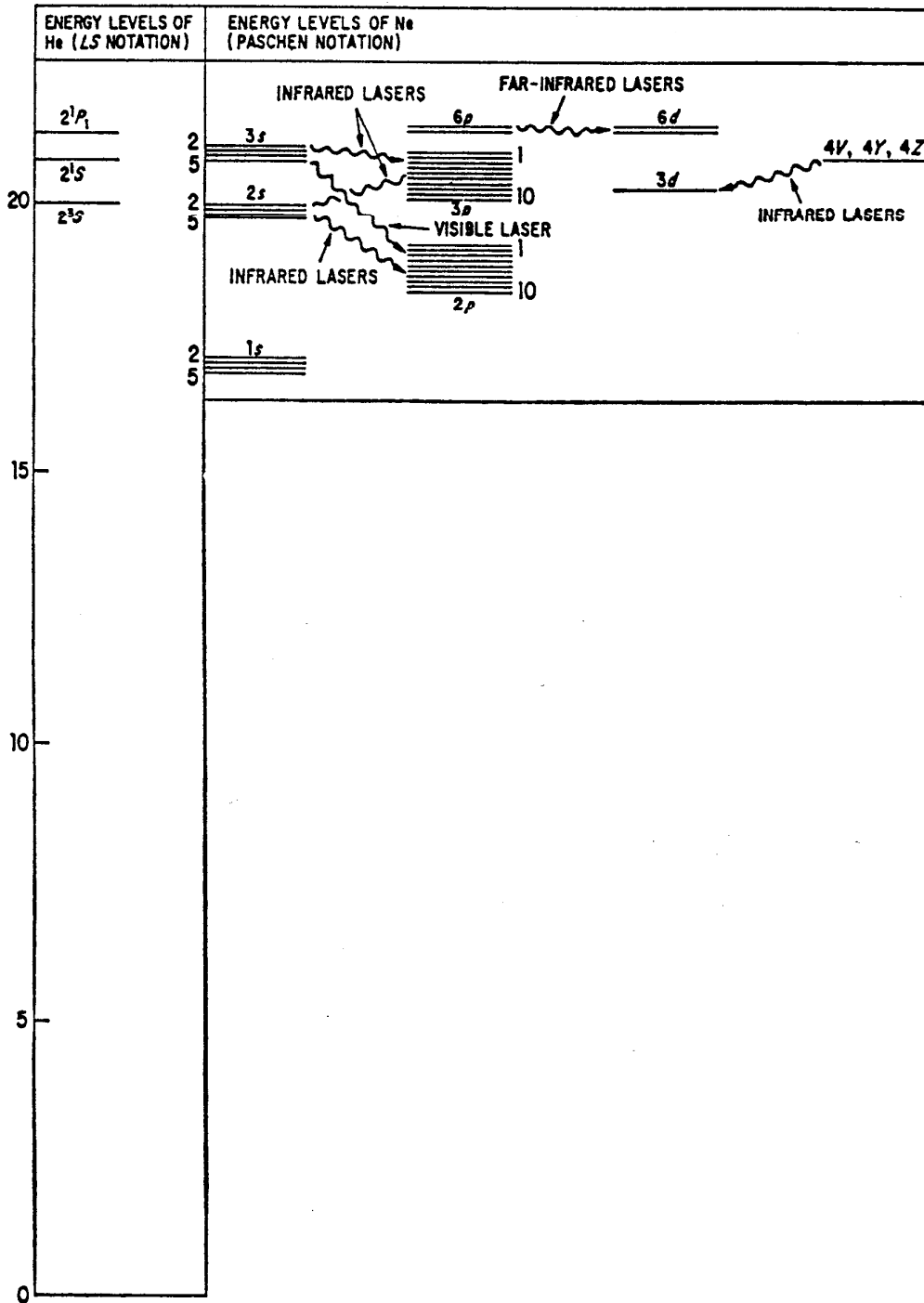


FIG. 6s-2. The energy levels to the He-Ne system.

laser excitation of the Ne occurs through collisions with excited He atoms; the appropriate energy levels are given in Fig. 6s-2. Specifically identified are only three of the more than 100 laser lines originating from the neon atom covering the range 0.5939 to 120 μm . The details of construction of a laser operating at these wavelengths involve pressures, discharge currents, tube diameter, and choice of cavity optics; however, typical parameters for 6,328 \AA or 1.15 μm are:

1. He⁺:Ne ratio, 10:1; total pressure, 2.5 torrs
2. Inside diameter, 2.0 mm
3. Radius of curvature of mirrors, 1 meter
4. Current 10 ma voltage, ~ 3 kv
5. Output, 5 mw
6. Mirror separation, ~ 1 meter

6s-3. Molecular Gases. The energy-level system of a molecular gas consists of subgroupings around each electronic state of vibrational and rotational energy levels. Spacing between vibration and rotation levels falls in the infrared region of the spectrum. At present, approximately 15 molecular gases have been shown to produce gain. A listing of those gases is given below, identifying the region of major lines.

TABLE 6s-2

Gas	Region of principal lines, μm
CO	5
CO ₂	10
H ₂ O	10-100

Until 1969, the CO₂ laser [32] has demonstrated the highest continuous output power. Reports of output powers in excess of 1,000 watts are common. A very convenient method of reaching high output power with a reasonable overall efficiency and size has recently been reported [19]. The specific details of pressure, current, etc., are dependent upon the dimensions. Although it is possible to excite the CO₂ directly through electron impact in a discharge, the usual way of producing the excited CO₂ for lasers is through a collision with excited N₂ molecules. A "typical" CO₂ laser configuration and operating parameters are given in Fig. 6s-3.

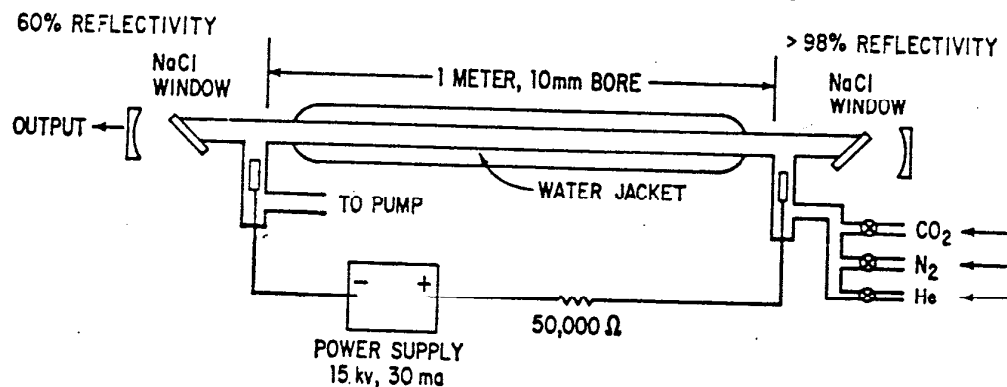


Fig. 6s-3. Schematic diagram of a CO₂ laser. The pressure maintained by the pump is approximately 10 torrs.

In the simple low-power system described electrical discharge is used to excite the N₂. Other means of exciting the CO₂ have been discussed. The most interesting seems to be thermal excitation [20,21] in flowing mixtures.

A persistent problem with the CO₂ laser in a "sealed-off" (i.e., fixed volume of gas) configuration has been a decay in output power with life. Advances in technique and understanding of the failure mechanism should alleviate this problem shortly.

For CO₂ lasers the appropriate energy levels are identified in Fig. 6s-4. Excitation of the CO₂ molecule from the ground state to the "001" level results from a collision with an excited N₂ molecule. This is followed by laser decay from the "001" level to the "100" level. Before recycling can occur, the CO₂ must decay back to the ground state.

6s-4. Ion Lasers. In an intense discharge it is possible to produce inverted populations among levels of the ions, and thus observe laser action. Most of the noble gases, the halogens, Group II and IV elements make up the two dozen ions that have been reported. Probably the most important is the argon or argon-krypton mixtures. The principal reason has been its convenient spectral region and relatively high output power. Continuous powers up to ~10 watts in mixtures of Ar and Kr have been

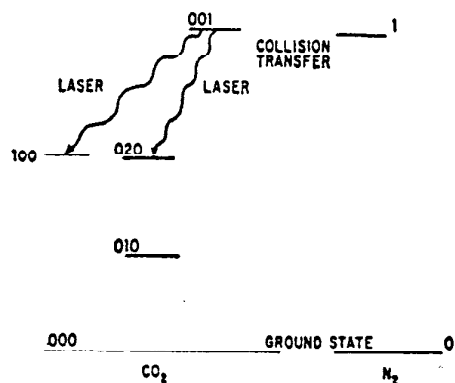


FIG. 6s-4. Appropriate energy levels for the CO₂:N₂:He laser system.

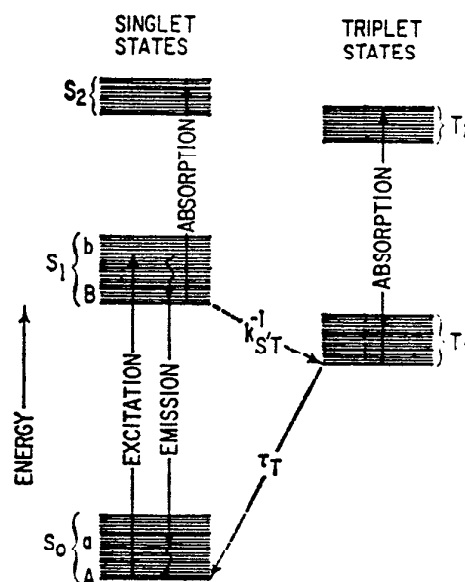


FIG. 6s-5. Energy levels for organic dye lasers.

reported. In this combination outputs of $\sim \frac{1}{4}$ watt are available at a series of lines from 4,800 to 6,471 Å.

6s-5. Organic Dye Lasers. The unique property of the organic dye lasers [25] that makes them of interest is their ability to be tuned [22] in frequency over portions of the visible spectrum. The materials used are given in Table 6s-3, along with the central wavelengths of laser emission. By using various frequency-selective devices within the cavity (e.g., etalon, gratings, or prisms) oscillation can be tuned over ~ 500 Å. These organic materials, in general, have two sets of electronic states, the singlet and triplet states, with the lower level a singlet (see Fig. 6s-5). The optical properties are determined by these levels. In transition between vibrational sub-levels, the single states have been observed to "lase." A "quenching action" is built in by the absorption of the triplet levels. Pumping has been accomplished with either other lasers or specially designed short flash lamps.

6s-6. Glass Lasers. The glass laser [26,29,30] in particular the Nd³⁺ doped glasses, is of particular interest because as a class they produce the highest peak powers and the shortest pulses. (See Table 6s-4).

In a glass rod one meter by 38 mm containing 3 percent by weight of Nd³⁺ doping an output of 5,000 joules in 3 ms has been reported [26]. Operation in a cw mode

TABLE 6s-3. STRUCTURE, WAVELENGTH, AND SOLVENTS FOR LASER DYES

Dye	Solvent	Wavelength, nm
Acridine Red.....	E ↑ OH	Red 600-630
Pyronin B.....	MeOH	Yellow
	H ₂ O	
Rhodamine 6G.....	E ↑ OH	Yellow 570-610
	MeOH	
	H ₂ O	
	DMSO	
	Polymethyl methacrylate	
Rhodamine B.....	E ↑ OH	Red 605-635
	MeOH	
	Polymethyl methacrylate	
Na-fluorescein.....	E ↑ OH	Green 530-560
	H ₂ O	
2,7-Dichlorofluorescein.....	E ↑ OH	Green 530-560
7-Hydroxycoumarin.....	H ₂ O	Blue 450-470
	(pH ~ 9)	
4-Methylumbelliferone.....	H ₂ O	Blue 450-470
	(pH ~ 9)	
Esculin.....	H ₂ O	Blue 450-470
	(pH ~ 9)	
7-Diethylamino-4-methylcoumarin.....	E ↑ OH	Blue
Acetamidopyrene trisulfonate.....	MeOH	Green-yellow
	H ₂ O	
Pyrylium salt.....	MeOH	Green

TABLE 6s-4. LASER IONS IN GLASS

Ion	Host	Wavelength, μm	Inversion for 1% gain/cm, cm ³
Nd ³⁺	K-Ba-Si	1.06	0.7×10^{18}
	La-Ba-Th-B	1.37	
	Na-Ca-Si	0.92	
Nd ³⁺	YAG	1.065	1.1×10^{16}
Yb ³⁺	Li-Mg-Al-Si	1.015	2.8×10^{18}
	K-Ba-Si	1.06	
Ho ³⁺	Li-Mg-Al-Si	2.1	
Er ³⁺	Yb-Na-K-Ba-Si	1.543	1.8×10^{18}
	Li-Mg-Al-Si	1.55	
	Yb-Al-Zn-P ₂ O ₅	1.536	
	Yb-fluorophosphate	1.54	
Tm ³⁺	Li-Mg-Al-Si	1.85	
	Yb-Li-Mg-Al-Si	2.015	

or at high pulse repetition rate is limited by the low thermal conductivity of glass. However, when the laser material is segmented as discs or slabs some relief from this problem is possible. One configuration using slabs has operated at 100 pulses/sec. The wide inhomogeneous fluorescent line width (180 Å) of Nd in glass makes it possible through a combination of Q-switching and mode locking to generate very

short pulses. To date the shortest pulse reported is 2.5×10^{-13} sec. In many applications not only is the pulse width important but the brightness watts/steradian $\cdot \text{cm}^2$ and the energy available. A recent report [7] is 51 joules in 3×10^{-13} sec or 17×10^{12} watts.

In designing to produce maximum brightness an essential feature is control of the cavity modes. The control in the form of a pinhole at the focus of a lens has been

TABLE 6s-5. SEMICONDUCTOR LASERS

Material	Photon energy, eV	Method of excitation
ZnS	3.82	Electron beam
ZnO	3.30	
CdS	2.50	
GaSe	2.09	Optical
CdS _x Se _{1-x}	1.80-2.50	Electron beam
CdSe	1.82	
CdTe	1.58	
Ga(As _x P _{1-x})	1.41-1.95	
GaAs	1.47	<i>p-n</i> junction
		Electron beam
		Optical
		Avalanche
InP	1.37	<i>p-n</i> junction
In _x Ga _{1-x} As	1.5	
GaSb	0.82	
		Electron beam
InP _x As _{1-x}	1.40	<i>p-n</i> junction
InAs	0.40	
		Electron beam
		Optical
InSb	0.23	<i>p-n</i> junction
		Electron beam
		Optical
Te	0.34	Electron beam
PbS	0.29	<i>p-n</i> junction
		Electron beam
PbTe	0.19	<i>p-n</i> junction
		Electron beam
		Optical
PbSe	0.145	<i>p-n</i> junction
		Electron beam
Hg _x Cd _{1-x} Te	0.30-0.33	Optical
Pb _x Sn _{1-x} Te	0.075-0.19	

used in a Pockels cell Q-switched oscillator-amplifier chain to generate 2×10^{17} w/cm². The overall efficiency of pulsed glass lasers is generally given as the ratio of the incremental pump energy in excess of threshold to the output power with glass lasers operating in the long pulse mode (pulse times $\sim 10^{-3}$ sec) efficiencies as high as 8 percent have been reported.

6s-7. Crystalline Solids. The first laser Cr³⁺:Al₂O₃ possessed all the general properties of this large class of lasers. They are characterized by impurities in low concentrations ($\sim 10^{-3} \rightarrow 10^{-2}$) and fluorescent emissions between $0.6 \rightarrow 2 \mu\text{m}$. Excitation of the fluorescent levels is through absorption bands lying at higher photon energies. At this time the two most commonly encountered are the Cr³⁺:Al₂O₃ and the Nd³⁺:YAG.

6s-8. Semiconductor Lasers. The first observations [28] of stimulated emission were obtained from forward-biased GaAs diodes. After this initial work other schemes of pumping were employed (e.g., optical pumping, electron beam, and avalanche breakdown). The range of materials is given in Table 6s-5, along with the approximate wavelengths of emission and the pumping systems. Several reviews have been written [27].

6s-9. Chemical Lasers. Various proposals have been to utilize the energy of exothermic chemical reactions to produce inverted populations of molecules. Examples of such reactions are the combination of H and F to form HF. Papers have been written reporting observations of laser action near 2.8 μm in HF [96] and in the transfer of energy obtained from the exothermic reaction of H and F forming HF to the CO₂ molecule [97].

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