Chapter 17

GAS LASERS

A relatively recent development in the field of gas-discharge devices is the gas laser. This device generates a highly directional beam of coherent light with perhaps a few milliwatts of power and with a line width, or frequency stability, which in principle can be made as small as a few cycles per second or a few tens of cycles per second. Before the invention of the laser, all available light sources, such as incandescent lights, fluorescent lights, and gas discharge sources, provided only incoherent light, that is, light in which the photons are emitted at random instants of time and with random phase. The light generated by the laser is a sinusoidal electromagnetic wave with a frequency stability which is determined largely by the dimensional stability of the device.

The brightness of a gas laser beam is enormously greater than that of non-laser light sources. Thus the sun, which radiates much like a black body with a temperature of 6000°K, has a total radiation at all wavelengths of about seven kilowatts per square centimeter of its surface. However, if it were possible to filter out a narrow band of light one kilocycle wide in the region of the spectrum where the sun has its peak output (at a wavelength of 4800 angstroms), the total power radiated within this narrow band would be only 10^{-8} watt per square centimeter of the sun's surface. The radiation per unit solid angle in the direction normal to the sun's surface would be $1/\pi$ times this power (see Equation (2.4-13)). In contrast, a gas laser might generate a beam with a few milliwatts of power in a band which in principle could be only a few cycles per second wide. The angular spread of the beam can be made less than one minute of arc. The gas laser therefore provides an entirely new and powerful tool in the field of optics, and it may well find a number of applications in the communications field.

The word "laser" is made up from the first letters of the words *light amplification by stimulated emission of radiation*. Stimulated emission refers to an interaction between an excited atom and an electromagnetic field in which the excited atom undergoes a transition to a state of lower energy and imparts the lost energy to the electromagnetic field. The process is the reverse of the more familiar phenomenon of light absorption by matter and, in fact, involves precisely the same physical concepts. For stimulated emission to occur, the frequency of the electromagnetic wave multiplied by Planck's constant h must equal the energy given up by the excited atom. Consider an atom which is excited to a state from which it can decay to a lower state by spontaneous emission of a photon $h\nu$. If an electromagnetic field is established in the region of the atom and if the frequency of the field is ν, the atom can decay to the lower state either by spontaneous emission of a photon $h\nu$ or by imparting the same amount of energy to the energy stored in the electromagnetic field. The latter process is called *stimulated emission.*

Suppose an electromagnetic wave propagates through a gas in which a fraction of the atoms are in either of two excited states, one with an energy $h\nu$ above the other and such that atoms in the upper state can decay to the lower state by spontaneous emission of a photon $h\nu$. The electromagnetic field causes some of the atoms in the upper state to decay to the lower state by stimulated emission. Similarly atoms in the lower state can *absorb* an amount of energy $h\nu$ from the electromagnetic field and become excited to the higher state. The probability per unit time of an atom in the lower state absorbing an amount of energy $h\nu$ and becoming excited to the higher state is equal to the probability per unit time of an atom in the upper state being stimulated by the field to undergo a transition to the lower state. This probability is proportional to the square of the field intensity of the electromagnetic wave.

In a noble gas at room temperature essentially all the atoms are in their lowest, or ground, state. Excitation to higher states can occur in several ways, for example, by establishing a dc discharge in the gas, by applying a high-frequency rf field of sufficient intensity to maintain a glow discharge in the region of the gas, or by irradiating the gas with light of a suitable wavelength. Suppose that by one of these mechanisms two excited states 1 and 2 are populated so that there are densities n_1 and n_2 atoms in these states per cubic centimeter of the gas. Suppose further that state 2 is of higher excitation energy than state 1, that atoms of state 2 can decay to state 1 by spontaneous emission of a photon $h\nu$, and that the conditions of the discharge are such that[1] $n_2 > n_1$. Then an electromagnetic wave of fre-

[1]As discussed subsequently in Section 17.1, atoms in a given excited state are characterized by a total angular momentum which may have several possible orientations relative to a particular direction of observation. These individual possible orientations of the total angular momentum are called magnetic substates. In the absence of a magnetic field, all magnetic substates have the same energy, and all are equally populated. In the above discussion the quantities n_1 and n_2 must be taken to be the populations of the individual magnetic substates of excited states 1 and 2.

quency ν passing through the gas will cause more atoms per unit volume and per unit time in state 2 to decay to state 1 by stimulated emission than it will cause atoms in state 1 to absorb $h\nu$ from the field and become excited to state 2. *There will therefore be a net addition of energy to the electromagnetic wave, and the wave is amplified in passing through the gas.*

Suppose next that optical reflecting surfaces are placed at either end of the discharge tube. If the surfaces are of such a spacing that there is an integral number of half wavelengths at the frequency ν between them, a standing-wave pattern can be established in which the waves are reflected forward and back across the discharge. Such a reflecting system for light waves is called a Fabry-Perot interferometer and is the optical equivalent of a cavity resonator for microwaves. When a standing wave pattern of wavelength c/ν is established in the region of the discharge, and when $n_2 > n_1$, energy is added to the electromagnetic wave by the discharge. The power level then builds up until the upper state is sufficiently depopulated by the electromagnetic wave that an equilibrium is reached between power added to the wave by gas discharge and power lost in reflection, diffraction, and absorption in the optical system.

Such a system is effectively an oscillator of frequency ν and is called a laser. If one of the reflectors transmits a small portion of the incident light ($\sim$1 per cent) rather than totally reflecting it, the transmitted beam is a sinusoidal electromagnetic wave of frequency ν and of frequency stability determined largely by the stability of the optical path length between the reflecting surfaces. Gas laser action has been observed to occur in a number of gases and between a number of pairs of excited states of these gases (see Table 17.3-1). The wavelengths corresponding to some of the transitions are in the visible spectrum, whereas others are in the infrared or ultraviolet regions.

If the light output from a laser is passed through a second discharge tube with the same gas filling and discharge conditions, so that $n_2 > n_1$, the light is *amplified* in passing through the discharge.

The first gas laser[2] used a gas filling consisting of a mixture of helium and neon. It happens that the excitation energies of two helium metastable states[3] very nearly coincide with the excitation energy of two excited states in neon. When a dc or rf discharge is established in the gas mixture, a high density of helium metastables is generated. These metastables collide with unexcited neon atoms causing excitation of the neon atoms to the excited neon states of nearly equal energy and causing the helium atoms to return

[2]Reference 17.1.

[3]A metastable state is an excited state from which spontaneous decay to a lower state is forbidden by the quantum-mechanical selection rules for electric-dipole transitions. (This does not necessarily preclude de-excitation by other processes or different types of transitions having a much smaller probability per unit time.)

to their ground state. The excited neon atoms can be stimulated to decay to a number of lower excited states, permitting laser action at a number of wavelengths ranging from the visible to the infrared region.

In the present chapter we shall first discuss the excited energy levels of atoms, particularly helium and neon, and we shall describe the balance of events occurring in laser action between two excited states of an atom. Then we shall describe a particular helium-neon laser and its performance, and we shall summarize briefly the range of performance and operating conditions presently obtained with other lasers.

17.1 Energy Levels in the Atoms

From quantum mechanics we learn that there are only certain discrete energies and angular momenta which the electrons that are bound to an atom can have. An atom in its ground state, or unexcited state, has all its electrons in the lowest possible energy states. As discussed in Section 2.1, for many purposes an electron in a given energy state can be thought of as causing a cloud of charge about the nucleus. The probability of finding an electron in a given volume element about the nucleus is proportional to the density of the cloud at the volume element. It is found that electrons in certain energy states tend to contribute their maximum charge density at approximately the same distance from the nucleus, and consequently there are said to be shells of electrons about the nucleus. Helium in its ground state has two electrons in a single shell about the nucleus. Neon in its ground state has two shells of electrons with two electrons in the inner shell and eight electrons in the outer shell. Argon in its ground state has three shells with two electrons in the inner shell, eight electrons in the next shell, and eight electrons in the outer shell.

Because electrons in the innermost shell of an atom are on the average closer to the nucleus than electrons in the next shell, greater energy is required to remove these electrons from the atom. Consequently electrons in the innermost shell are said to be in states of lower energy than electrons in the next shell. Similarly, in atoms with three or more shells, electrons in the second shell are more tightly bound to the atom than electrons in the third shell, and so on. However, an experimental law of physics, known as the Pauli exclusion principle, prohibits all the electrons in the atom from going into the states of lowest energy and hence into the shell which is closest to the nucleus. Only two electrons can go into the inner shell, whereas up to eight electrons can go into the second shell, and up to eighteen can go into the third shell.

The fact that there are shells of electrons about the nucleus is directly related to the quantization of the electron motions. It is customary in the field of spectroscopy to describe an electronic state by means of two quantum numbers n and l. The quantum number n is related to the average radial distance of the electron orbit from the nucleus and hence to the shell that the electron is in. The number n may have integral values 1, 2, 3 . . . . An electron in a state for which $n = 1$ is in the innermost shell of the atom, an electron in a state for which $n = 2$ is in the next shell, and so on. The quantum number l indicates the oribital angular momentum of the electron about the nucleus. This angular momentum is given by $\sqrt{l(l+1)}\ h/2\pi$, where h is Planck's constant. l can have values 0, 1, 2, . . . $n - 1$. The atomic spectroscopists further use the letters s, p, d, and f to correspond to $l = 0, 1, 2,$ and 3. Thus the electronic configuration of an unexcited helium atom is given by $(1s)^2$, where $1s$ indicates a state with $n = 1$ and $l = 0$, and the superscript 2 indicates that two electrons are in this state. The electronic configuration of the ground state of neon is written as $(1s)^2\ (2s)^2\ (2p)^6$, indicating that there are two electrons in $1s$ ($n = 1$, $l = 0$) states, two electrons in $2s$ ($n = 2$, $l = 0$) states, and 6 electrons in $2p$ ($n = 2$, $l = 1$) states. An excited neon atom might have one of the $2p$ electrons raised to a $3s$ level The electronic configuration for the atom in this case would be $(1s)^2\ (2s)^2\ (2p)^5\ 3s$. The excited electron might also be raised to any of the following states: $3p$, $3d$, $4s$, $4p$, $4d$, $4f$, $5s$, $5p$, etc. Radiative transitions can occur only between states whose values of l differ by ± 1.

The energy levels are not determined uniquely by the quantum numbers n and l. Electrons also have an intrinsic spin angular momentum, and interactions between this angular momentum and the orbital angular momenta lead to a splitting of the excitation energies into closely spaced groups of states. Finally, each of these states is characterized by a total angular momentum which is a vector sum of the spin and orbital angular momenta of all the electrons of the atom. The total angular momentum is characterized by a quantum number J such that the total angular momentum is equal to $\sqrt{J(J+1)}\ h/2\pi$, where h is Planck's constant. If there are an even number of electrons in the atom, J is an integer, and if there are an odd number of electrons in the atom, J has a value equal to one half an integer. The total angular momentum can have $2J + 1$ possible components in any direction of observation. For example, if J is 2, the total angular momentum along a direction of observation can be $-2h/2\pi$, $-1h/2\pi$, 0, $+1h/2\pi$, or $+2h/2\pi$. These individual possible orientations of the total angular momentum are referred to as *magnetic substates*. In an applied magnetic field, the energies of the magnetic substates are separated by an amount proportional to the magnetic field intensity. In the absence of a magnetic field, all magnetic substates have the same energy, and all are equally populated. In the introductory part of this chapter we referred to population densities n_1 and n_2 for two excited states, 1 and 2. As noted[1], these population densities must be taken to mean the density of atoms in any one magnetic substate of excited states 1 and 2. Thus, if N_1 is the *total* density of atoms in state 1 and if there is no externally applied magnetic field, $n_1 = N_1/(2J + 1)$.

It is not possible to make an exact quantum mechanical calculation of the energy levels in an atom with more than one electron because the forces acting on an individual electron result not only from the nucleus but also from all the other electrons, and the motion of each electron affects the motions of all the other electrons. However, calculations involving a number of approximations have been made, and the energy levels can be measured with a high degree of accuracy by spectroscopic observations.

Figure 17.1-1 shows a graphical presentation of the energy levels of the lower excited states in helium and neon. It is assumed in this plot that only one electron is excited. Each excited level in neon is actually broken into a group of closely spaced states which result from different possible orientations of the electron spin and orbital angular momenta. The lowest excited states in neon are four 3s states in the neighborhood of 16.7 electron volts. An excited atom in one of these states has the configuration $(1s)^2\ (2s)^2\ (2p)^5$

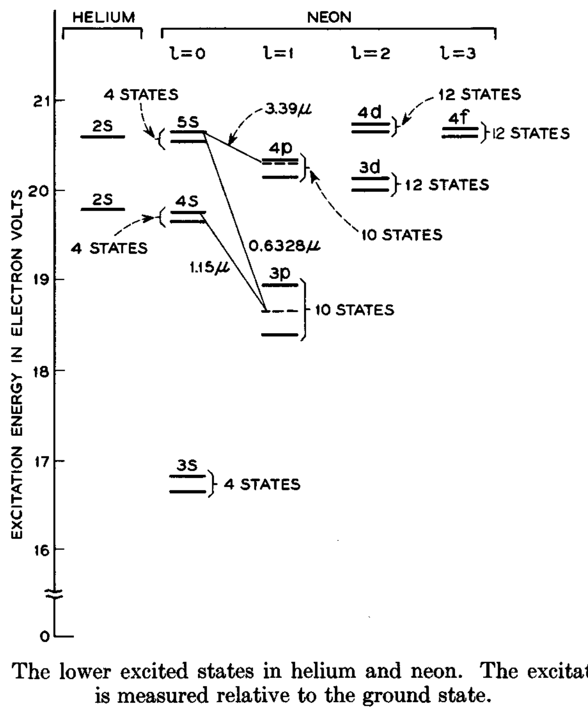

FIG. 17.1-1 The lower excited states in helium and neon. The excitation energy is measured relative to the ground state.

3s. The splitting of the 3s state into four states results from different orientations of the spin angular momenta relative to the orbital angular momenta. Each of the four 3s states is characterized by a particular value of the total angular momentum quantum number J. This in turn leads to $2J + 1$ magnetic substates for each of the four 3s states. The next higher states are ten 3p states in the neighborhood of 18.7 electron volts. The electronic configuration for these states is $(1s)^2\ (2s)^2\ (2p)^5\ 3p$.

The lowest excited states in helium are two 2s states which differ in energy because the electron spin angular momenta are parallel in one case (the state of lower energy) and opposed in the other case. Both these states are metastable. Their excitation energies very nearly coincide with those of the 4s and 5s states in neon. In the operation of the helium-neon laser, the helium 2s metastables are destroyed largely by collisions with ground-state neon atoms. In these collisions the excitation energy of the metastable helium atom is transferred to a neon atom, thereby exciting it to the 4s or 5s state. Laser action can then occur in neon between 5s and 4p states, between 5s and 3p states, and between 4s and 3p states. Three wavelengths frequently observed with helium-neon lasers are shown in Figure 17.1-1 The wavelengths are measured in microns (symbol μ). $1\mu = 10^{-6}$ meter $= 10^4$ angstroms.

17.2 Operation of a Laser

It will be helpful to express in equation form the balance of events that occur in laser action between two excited states of an atom. Our objective will be to derive an expression for the power output of light from one end of the laser in terms of certain parameters of the discharge. Figure 17.2-1 shows an energy level diagram in which laser action is assumed to take place between two excited states, 1 and 2. We shall use the following quantities:

n_1 and n_2 are the population densities, or numbers of atoms per cubic centimeter, in states 1 and 2.

$\dot{n}_1$ and $\dot{n}_2$ are the time rates of change of the population densities n_1 and n_2.

S_1 and S_2 are the rates at which atoms in states 1 and 2 are produced by the discharge per cubic centimeter of gas. S_1 is assumed to account for all means of generating atoms in state 1 except spontaneous decay of atoms in state 2 to state 1. We shall consider spontaneous decay from state 2 to state 1 separately.

A_1 and A_2 are the probabilities per unit time of atoms in states 1 and 2 decaying by spontaneous emission.

A_{21} is the probability per unit time of an atom in state 2 decaying to state 1 by spontaneous emission.

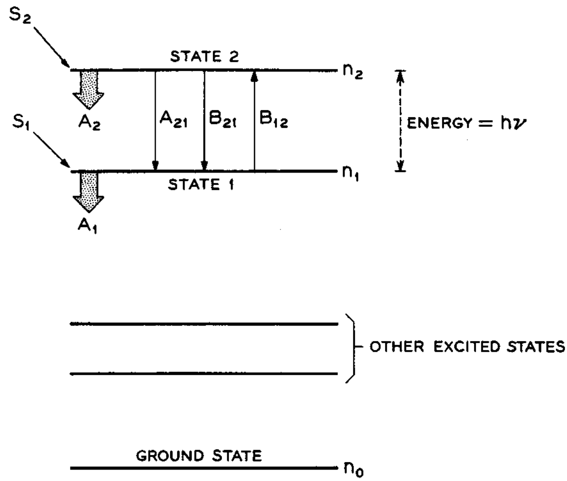

FIG. 17.2-1 An energy level diagram showing the excitation energies of a hypothetical atom measured relative to the ground state.

P is the electromagnetic power crossing a square centimeter of a plane normal to the direction of propagation of the wave.

B_{12} and B_{21} are the stimulated emission coefficients for transitions from states 1 to state 2 and for transitions from state 2 to state 1. The coefficient B_{12} is such that $B_{12}P$ is the probability per unit time that an atom in state 1 will be stimulated to absorb energy $h\nu$ from the electromagnetic field and become excited to state 2. $B_{21}P$ is the probability per unit time that an atom in state 2 will be stimulated by the electromagnetic field to decay to state 1. The coefficients B_{12} and B_{21} are equal.

The quantities A_1, A_2, A_{21}, B_{12}, and B_{21} are functions of the electronic configuration of the individual states.

The time rates of change of the population densities n_1 and n_2 are given by

$$\dot{n}_1 = S_1 + n_2(A_{21} + B_{21}P) - n_1(A_1 + B_{12}P) \tag{17.2-1}$$

and

$$\dot{n}_2 = S_2 - n_2(A_2 + B_{21}P) + n_1B_{12}P \tag{17.2-2}$$

In the steady-state condition,

$$\dot{n}_1 = \dot{n}_2 = 0 \tag{17.2-3}$$

Combining the above three equations and solving for $n_2 - n_1$, we obtain

$$n_2 - n_1 = \frac{S_2(A_1 - A_{21}) - S_1A_2}{A_1A_2 + B_{21}P(A_1 + A_2 - A_{21})} \tag{17.2-4}$$

where we have made use of the equality $B_{12} = B_{21}$.

The power P increases with distance x in the direction of propagation if $n_2 > n_1$ and decreases if $n_2 < n_1$. We can write

$$\frac{dP}{dx} = h\nu B_{21}P(n_2 - n_1) = \frac{\alpha P}{1 + \eta P} \qquad (17.2\text{-}5)$$

where

$$\alpha = \frac{h\nu B_{21}}{A_1A_2}[S_2(A_1 - A_{21}) - S_1A_2] \qquad (17.2\text{-}6)$$

and

$$\eta = B_{21}\left(\frac{1}{A_1} + \frac{1}{A_2} - \frac{A_{21}}{A_1A_2}\right) \qquad (17.2\text{-}7)$$

In the small-signal case in which a weak electromagnetic wave passes through the gas, $\eta P \ll 1$, and $dP/dx = \alpha P$, or

$$P = P_o\epsilon^{\alpha x} \qquad (17.2\text{-}8)$$

where P_o is the electromagnetic power crossing a square centimeter of a plane normal to the direction of propagation at $x = 0$. The power of the electromagnetic wave therefore builds up exponentially with distance in the direction of propagation. However, as ηP approaches unity, $n_2 - n_1$ decreases, and dP/dx is no longer proportional to P.

Suppose that reflecting mirrors are placed at opposite ends of the discharge tube and that a fraction t of the light incident upon the mirrors is transmitted through the mirrors. We shall assume that t is small compared with unity ($\sim$1 per cent) and that a fraction $1 - t$ of the light incident upon the mirrors is reflected without loss. The particular laser we are considering therefore generates a beam of equal intensity from both ends of the discharge tube. In the steady-state condition, the standing wave field pattern between the mirrors can be resolved into two traveling waves, one traveling to the left and one traveling to the right between the mirrors. The power gain of one of these waves in traveling the distance L between the mirrors must equal the power lost in reflection, and hence the power transmitted through the mirror. The power transmitted through the mirror is tP per square centimeter of the mirror, where P is the light power incident upon a square centimeter of the mirror. The quantity tP is small compared with P, so that the power gain in traveling the distance between mirrors is also small compared with P. Accordingly we can use Equation (17.2-5) to express this power gain as

$$\frac{dP}{dx}L = \frac{\alpha PL}{1 + \eta P} \qquad (17.2\text{-}9)$$

Equating the right-hand side of the equation to tP and solving for tP, we obtain

$$tP = \frac{t}{\eta}\left(\frac{\alpha L}{t} - 1\right) \tag{17.2-10}$$

This expression gives the light power output per square centimeter from one end of the laser in terms of the quantities α, η, and t. The quantities α and η are related to S_1, S_2, A_1, A_2, and A_{21} through Equations (17.2-6) and (17.2-7)

17.3 A Helium-Neon Gas Laser

Figure 17.3-1 shows the construction of a particular helium-neon gas laser. The helium-neon gas mixture is contained within a discharge tube which has windows at either end and which has a relatively long positive-

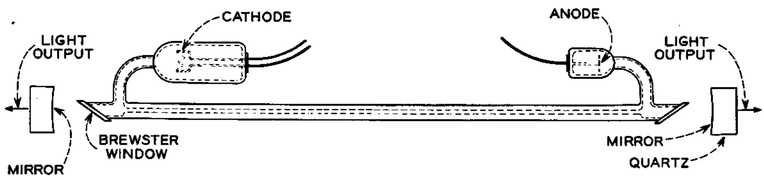

FIG. 17.3-1 The construction of a helium-neon laser.

column region. The cathode and anode are mounted to one side of the tube axis. Precision mirrors coated to reflect red light are mounted beyond the windows at the ends of the discharge tube in such a manner that they reflect light forward and back along the tube. The mirrors are only partially reflecting (~99 per cent), so that a small amount of light (~1 per cent) is transmitted through them. The transmitted light provides the power output of the device. The light output is visible and has a wavelength of 0.6328 micron.

The discharge tube is filled with a mixture of helium and neon, consisting of seven parts of helium mixed with one part of neon. The filling pressure is 1.8 mm of Hg. The inside diameter of the long glass tube is 2 mm, and the length of the straight portion of the tube is 30 cm. The discharge is operated at a current of approximately 10 ma, which corresponds to an anode-to-cathode voltage drop of 1300 volts. The cathode consists of a directly heated nickel mesh with an oxide coating. The anode is made of nickel.

At both ends of the discharge tube there are fused quartz windows, called Brewster windows. Each window is inclined relative to the tube axis such that the normal to the window makes an angle of 55.5 degrees with the tube axis. At this angle the reflection of 0.6328-μ light polarized in a plane containing the tube axis and the normal to the window is a minimum. The angle is known as the Brewster angle[4]. The light transmission through the windows for this wavelength and polarization is approximately 99.9 per cent for each passage through a window. The transmission of light polarized in a direction perpendicular to the plane containing the tube axis and the normal to the windows is much less, and consequently laser action does not take place for such light. The windows are about 2 mm thick and polished on both faces to a flatness of better than 800 angstroms.

Each mirror consists of a highly polished fused quartz surface onto which is evaporated alternate layers of a material of high index of refraction (ZnS) followed by a material of low index of refraction ($ThOF_2$). Each layer is a quarter wavelength thick at 0.6328 μ, the outer layer being of the material of a high index of refraction. Reflections from each interface beneath the surface add in phase to the wave reflected from the outer surface and increase the total light reflection. The mirrors used in the laser shown in Figure 17.3-1 consist of 7 layers of ZnS and six layers of $ThOF_2$. Such a mirror transmits about 0.7 per cent of the incident light, whereas less than 0.5 per cent is absorbed or scattered, and the remainder is reflected. The surface of the mirrors is slightly concave with a radius of curvature of 3 meters. The curvature serves to focus the reflected light in the direction of the opposite mirror and reduces the loss of radiation by diffraction effects.

Light is reflected between the mirrors at either end of the discharge tube, and for wavelengths at which the optical distance between the mirrors is an integral number of half wavelengths, a standing-wave pattern is established. The two mirrors therefore serve as a sort of cavity resonator. When such a system is constructed using plane mirrors, it is called a *Fabry-Perot interferometer*. At the resonant wavelengths, successive reflections from the mirrors add in phase. If the frequency of one or more of the resonant modes lies within the frequency range of a neon transition between two excited states, and if the upper state has a sufficient excess population over the lower state, laser action can occur.

Let L be the optical spacing between the mirrors. The resonant frequencies of the Fabry-Perot interferometer are such that

$$\frac{2L}{\lambda} = \frac{2L}{c}\nu = n \qquad (17.3\text{-}1)$$

or

$$\nu = \frac{nc}{2L} \qquad (17.3\text{-}2)$$

[4]The Brewster angle $\theta(\lambda)$ for a given wavelength of radiation λ is such that $\tan\theta(\lambda)$ equals the index of refraction of the window material for the wavelength λ.

where n is an integer, ν and λ are the frequency and wavelength of the radiation, and c is the velocity of light. In the laser shown in Figure 17.3-1 the distance L is approximately 37 cm. With such a spacing between planar mirrors, the resonant frequencies are separated by $c/2L = 400$ Mc.

The frequency stability of the laser shown in Figure 17.3-1 is determined principally by the stability of the optical path L between the mirrors. Differentiating Equation (17.3-2) with respect to L, we obtain

$$d\nu = -\frac{ncdL}{2L^2} = -\frac{\nu}{L}dL \qquad (17.3\text{-}3)$$

or

$$\frac{d\nu}{\nu} = -\frac{dL}{L} \qquad (17.3\text{-}4)$$

For a change in optical path $dL = 1$ ansgtrom $= 10^{-8}$ cm (about a quarter of an atomic diameter) in a length L of 37 cm, we obtain $d\nu/\nu = 10^{-8}/37 = 2.8 \times 10^{-10}$. Frequency stabilities of this magnitude or better are attainable using various frequency control schemes or by careful isolation of the laser from all mechanical disturbances. In principle it should be possible to stabilize the frequency to within a range of a few cycles per second. On the other hand, the frequency can be modulated in accordance with Equation (17.3-4) by attaching one of the mirrors to an electromechanical transducer which causes the distance L to vary in response to an applied electrical signal.

Operation of the Laser Shown in Figure 17.3-1

At a discharge current of 10 ma, both helium and neon ions take part in the current conduction, and the anode-to-cathode voltage drop is found to be intermediate between that of a pure neon discharge with the same partial pressure and a pure helium discharge with the same partial pressure. The discharge leads to the generation of a relatively high density of helium metastables in the two helium metastable states ($\sim 3 \times 10^{11}/\text{cm}^3$). The metastables are formed by electron collisions with helium atoms in which the atom is excited either directly to the metastable level or to a higher level from which it decays by one or more radiative transitions to the metastable level.

The metastables in turn diffuse through the gas mixture until they are destroyed by one of the following processes: (1) collisions with neon atoms in which the neon atom is excited to a $4s$ or $5s$ state, (2) collisions with the walls of the discharge tube, and (3) collisions with free electrons in which the metastable is excited to a higher state. Primarily the metastables are lost by the first of these processes, and consequently neon atoms are excited to the $4s$ and $5s$ levels at a relatively high rate.

In the absence of an electromagnetic field, excited neon atoms in a 5*s* state decay to 4*p* and 3*p* states by spontaneous emission of a photon. Atoms in 4*p* states in turn decay to 3*d*, 4*s*, 3*s* states, or the ground state, by spontaneous emission of a photon, and atoms in 3*p* states decay to 3*s* states or the ground state by spontaneous emission of a photon.[5] The probability per unit time of an excited atom in a 4*p* or 3*p* state decaying by spontaneous emission of a photon is sufficiently large that in the absence of an electromagnetic field the population of excited neon atoms in 4*p* or 3*p* states is less than the population of excited neon atoms in 5*s* states. The laser shown in Figure 17.3-1 actually exhibits laser action simultaneously between the 5*s* and 3*p* levels in neon leading to the generation of 0.6328-μ light, and between the 5*s* and 4*p* levels leading to the generation of 3.39-μ light.

In the emission spectrum of neon the half-power width of the 0.6328-μ line is found to be approximately 1.5 Gc, expressed as a frequency. This width results primarily from the well-known Doppler effect. In the discussion following Equation (17.3-2) it was noted that the resonant frequencies of the cavity illustrated in Figure 17.3-1 are separated by 400 Mc. Thus there are approximately three resonant frequencies within the width of the 0.6328-μ line. In consequence of this, the laser illustrated in Figure 17.3-1 exhibits laser action at three closely spaced wavelengths within the Dopper width of the 0.6328-μ line. From Equation (17.3-2) it is evident that the frequency spacing of these "modes" of oscillation increases as the optical distance L between the mirrors is reduced. Thus lasers have been constructed with about one third the length of the device shown in Figure 17.3-1 which give laser action in only one mode. In these devices the frequency spacing between modes is approximately equal to the Doppler width of the 0.6328-μ line.

The quantity α in Equation (17.2-8) has been measured for 0.6328-μ light and for the discharge conditions of the device illustrated in Figure 17.3-1. The frequency of the light was at the center of the Doppler width of the line. The quantity α was found to be approximately 0.14 per meter, corresponding to a gain of about 15 per cent per meter of travel through the gas. The corresponding value of $n_2 - n_1$ for small P has been calculated to be[6] 3.9×10^9 per cm^3. For the $5s - 4p$ transition leading to the generation of 3.39-μ light, α has been measured in a discharge tube with an inside diameter of 6 mm and found to be $\geqslant 4$ per meter, corresponding to a power gain of $\geqslant 52$ per meter. The corresponding value of $n_2 - n_1$ has been calculated to be $\geqslant 9 \times 10^8$ for small P.

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[5]Not all 3*p* and 4*p* states have quantum-mechanically allowed transitions to the ground state.

[6]Reference 17.2.

One way to prevent laser action at a particular wavelength while maintaining it at another wavelength is to use prisms between the Brewster windows and the mirrors, as illustrated in Figure 17.3-2(a). By orienting the prisms at an appropriate angle, operation at the desired wavelength can be obtained. The function of the prism and mirrors also can be combined, as shown in Figure 17.3-2(b).

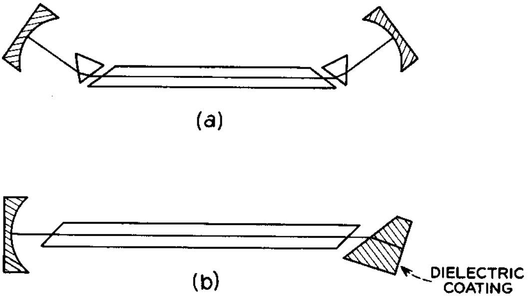

FIG. 17.3-2 By the use of prisms, the laser action can be limited to a single wavelength.

The total light power output of the laser shown in Figure 17.2-1 for the three modes in the neighborhood of 0.6328-μ is approximately 3 mw at a discharge current of 10 ma. Many design parameters besides the length L of the discharge tube affect this power output. These include: the diameter of the discharge tube, the filling pressure, the ratio of helium to neon, as well as the discharge current. However consideration of these parameters is beyond the scope of the present discussion.

The beam spread of the light transmitted through the mirrors is of the order of several minutes of arc. However this spread can be reduced with the aid of a lens to approximately λ/d, where d is the diameter of the discharge tube. For $\lambda = 0.6328 \times 10^{-4}$ cm and $d = 0.2$ cm, λ/d is approximately one minute of arc.

17.4 Other Gas Lasers

For laser action to occur in a gas one must establish an "inverted population" for two excited states between which spontaneous emission can occur. By "inverted population" we mean that the magnetic substate population of the upper state must exceed that of the lower state. In the helium-neon laser the 5s neon state is populated largely by excitation of neon atoms to the 5s state in collisions with helium metastables.

Inverted populations also can be obtained in dc discharges in the pure noble gases as well as in molecular gases. Finally, inverted populations have been obtained in cesium by irradiating a tube containing cesium vapor with light from an adjacent helium discharge tube. It turns out that the photon energy of one of the stronger spectral lines observed in the helium discharge falls within the Doppler width of the excitation energy of a cesium state, and by irradiating the cesium with this helium light, excitation of the cesium atoms occurs and laser action for two transitions has so far been observed.

In Table 17.4-1 we have attempted to summarize the numbers of lines in the various gases for which laser action, either pulsed or continuous, has been observed. The minimum and maximum wavelengths for these

TABLE 17.4-1

Gas	*Number of Lines Observed*	*Range of Wavelengths, Microns*
He	1	2.06
Ne	117	0.59–133
A	31	1.62–26.9
A^+	10	0.45–0.53
Kr	25	1.69–7.06
Xe	27	2.03–18.5
O	1	0.85
C	2	1.07–1.45
N	2	1.36–1.45
N_2	Several tens of transitions	0.3–1.2
S	2	1.05–1.06
Hg	2	1.53–1.81
Cl	2	1.97–2.02
Br	4	0.85
I	2	3.24–3.43
Cs	2	3.20–7.18
CO	20	0.56–0.66
H_2O	9	23.3–78.8
CO_2	21	9–11

lines for each gas is also listed. At the time of writing, investigation of laser action in gases is proceeding at such a rapid rate that the listing will be out of date by the time this textbook has been printed. However the table will serve to indicate the extent of the published investigations as of early 1964.

The lines observed in A^+ are transitions between excited states of singly ionized argon. Laser action has been observed for atomic nitrogen (N) transitions and for molecular nitrogen (N_2) transitions. It turns out that the lower state for the N_2 and CO transitions is metastable, so that as laser action proceeds, the population of the lower state increases, and the inverted population soon vanishes. Laser action is therefore observed using a pulsed discharge and is found to occur for only a fraction of a microsecond at the start of the pulse.

REFERENCES

A more extensive description of gas laser principles is given in the following reference:

17a. W. R. Bennett, Jr., *Appl. Optics*, Supplement 1: Optical Masers, p. 24, 1962.
17b. Bela A. Lengyel, *Lasers*, John Wiley and Sons, Inc., New York, 1962.

Other references covering specific topics discussed in this chapter are given below.

17.1 A. Javan, W. R. Bennett, Jr., and D. R. Herriott, *Phys. Rev. Letters* **6**, 106, 1961.
17.2 W. L. Faust and R. A. McFarlane, private communication.