regions producing laser light. Thus, in semiconductor lasers, a direct conversion of electrical energy into light energy takes place.

(c) X-ray Pumping :

In some cases atoms of solids can be excited by X-ray beam and pumping can be achieved.

(d) Chemical Pumping :

When excitation is produced by exothermic chemical reactions, it requires highly reactive and often explosive gaseous mixture.

1.30 ACTIVE MEDIUM

Atoms in general are characterized by a large number of energy levels. However, all types of atoms are not suitable for laser operation. Even in a medium consisting of different species of atoms, only a small fraction of atoms of a particular species are suitable for stimulated emission and laser action. Those atoms which cause light amplification are called *active centers*. The rest of the medium acts as host and supports active centers. The medium hosting the active centers is called an *active medium. An active medium is thus a medium which, when excited, reaches the state of population inversion, and eventually causes light amplification.* The active medium may be a solid, a liquid or a gas.

1.31 METASTABLE STATES

An atom can be excited to a higher level by supplying energy to it. Normally, excited states have short lifetimes and release their excess energy in a matter of nanoseconds (10^{-9} sec) by spontaneous emission. Atoms do not stay at such excited states long enough to be stimulated to emit their energy. Though, the pumping agent continuously raises the atoms to the excited level, many of them rapidly undergo spontaneous transitions to the lower energy level. Population inversion cannot be therefore established. For establishing population inversion, the excited atoms are required to " wait" at the upper lasing level till a large number of atoms accumulate at that level. Thus, what is needed is an excited state with a longer lifetime. Such longer-lived upper levels from where an excited atom does not return to lower level at once, but remains excited for an appreciable time, are known as *metastable states.* Phosphors are an example of materials having metastable states. They emit persistent light called *phosphorescence* because of metastable states existent in them.

Atoms stay in metastable states for about 10^{-6} to 10^{-3} s. This is 10^3 to 10^6 times longer than the time of stay of atom at excited levels. Therefore , it is possible for a large number of atoms to accumulate at a metastable level. The metastable state population can exceed the population of a lower level and lead to the state of population inversion.

If the metastable states do not exist, there could be no population inversion, no stimulated emission and hence no laser operation.

Thus, the foundation to the laser operation is the existence of metastable states.

1.32 PUMPING SCHEMES

Atoms in general are characterized by a large number of energy levels. Among these energy levels, two, three or four levels will be pertinent to the pumping process. Accordingly, pumping schemes are classified as two-level, three-level and four-level schemes. Among them, the two-level scheme will not lead to laser action. The three-level and four-level schemes are important and are widely employed.

(a) Two Level Pumping Scheme :

It appears that the most simple and straight-forward method to establish population inversion is to pump an excess of atoms into the higher energy state by applying intense radiation. But basically, a two-level pumping scheme, shown in Fig. 1.9, is not suitable for attaining population inversion. We can establish it through the following considerations.

Population inversion requires a build-up of population in the upper laser level. It is possible only if the upper level is populated faster than it decays, so that the population of the upper level exceeds that of the lower level. It, in turn, is possible only if the lifetime of spontaneous emission is longer. Thus, it is required that the lifetime Δt at upper level E_2 must be longer. According to Heisenberg uncertainty principle, the linewidth ΔE_2 of level E_2 and the lifetime Δt are related by.

$$\Delta E_2 \, . \, \Delta t \geq \hbar \qquad ...(1.84)$$

Δt will be longer if ΔE_2 is smaller which implies that the upper energy level E_2 must be narrow. However, if E_2 is narrow, we have to use only a specific frequency photon $(\nu = E_2 - E_1/\hbar)$ to pump atoms. It means that the pump source should be highly monochromatic. In practice, monochromatic source of required frequency may not exist. Even if it exists, the pumping efficiency would be very low. The result is that enough population cannot be excited to level E_2. Further, pumping radiation on one hand excites the ground state atoms and on the other hand induces transitions from the upper level to the lower level. It means that pumping operation simultaneously populates and depopulates the upper level. Hence, population inversion cannot be attained in a two-level scheme. All that we may achieve at best is a system of equally populated levels.

One must therefore look for materials with either three or four energy level systems, which operate with *different frequencies* of pumping and lasing transitions.

The transition between the two levels that generate stimulated emission is called a *lasing transition*. The terminal level is called the *lower lasing level* and the upper level as *upper lasing level*. The upper lasing level should be a metastable level. The uppermost level to which atoms are excited is known as the *pumping level*. The transition between the ground level and the pump level is called the *pump transition*.

(*b*) Three Level Pumping Scheme :

A model of a three level pumping scheme is illustrated in Fig. 1.22. A three level scheme is one in which the lower laser level is either the ground state or a level whose separation from the ground state is small compared to kT.

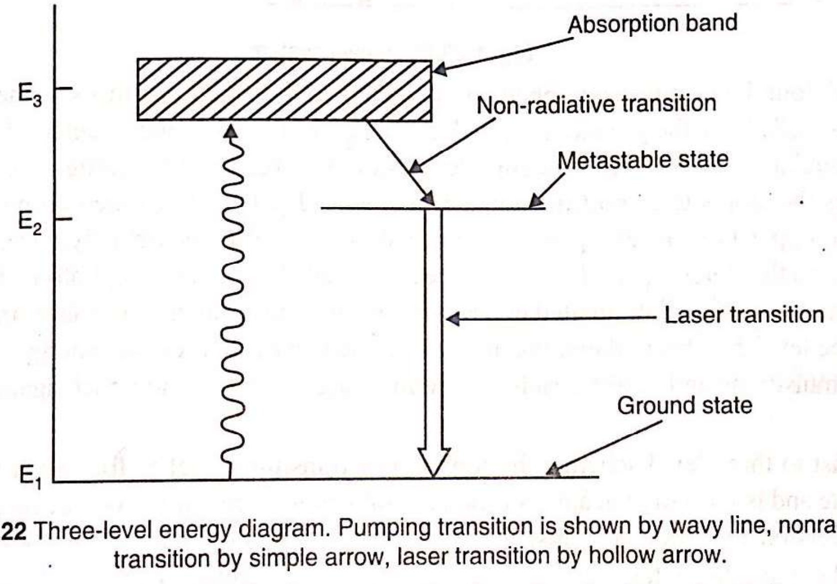

Fig. 1.22 Three-level energy diagram. Pumping transition is shown by wavy line, nonradiative transition by simple arrow, laser transition by hollow arrow.

Initially, the population distribution among the three levels obeys the Boltzmann law. When the atoms are subjected to an intense radiation of pumping frequency $\nu_p = (E_3 - E_1/h)$, the atoms are pumped to the higher level E_3. Some of the excited atoms make spontaneous transitions to the ground state but many of them undergo spontaneous non-radiative transitions to the metastable level E_2. As spontaneous transitions from E_2 to E_1 do not occur often, the atoms accumulate at the metastable level E_2. The build-up of atoms at E_2 continues because of pumping process. Eventually, the population N_2 at E_2 exceeds the population N_1 at E_1 and population inversion is attained. Now, a photon of $h\nu$ (= $E_2 - E_1$) can induce stimulated emission and laser action.

For better pumping efficiency, the level E_2 should be a band of energy levels instead of being a single narrow line. It allows use of a pumping radiation of wider bandwidth to excite more atoms. However, the major disadvantage of a three level scheme is that it requires very high pump powers. In this scheme, the terminal level of the laser transition is simultaneously the ground state. Therefore, inversion of population requires more than half of the ground state atoms to be lifted to the higher energy level. As the ground state is heavily populated, large pumping power is to be used to depopulate the ground level to the required extent.

The three level scheme can produce light only in pulses. Once stimulated emission commences, the metastable state E_2 gets depopulated very rapidly and the population of the ground state increases quickly. As a result the population inversion ends. One has to wait till the population inversion is again established. Thus, three level lasers operate in *pulsed mode.*

(c) Four Level Pumping Scheme

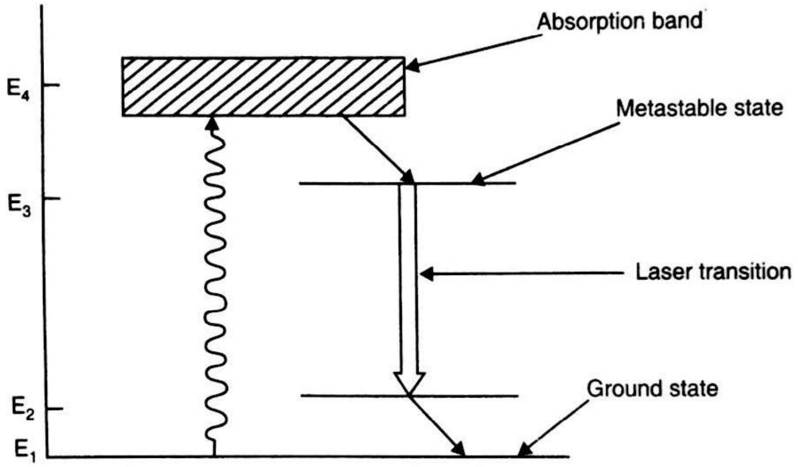

Fig. 1.23 Four-level system

A typical four level pumping scheme is depicted in Fig. 1.23. In this scheme, the terminal laser level E_2 is well above the ground level such that ($E_2 - E_1$) >> kT. It guarantees that the thermal equilibrium population of E_2 level is negligible. As in the three level pumping scheme, the pump energy elevates the atoms to a short lived uppermost level E_4. The atoms then drop spontaneously to a metastable upper laser level E_3. As the terminal laser level E_2 is virtually vacant, population inversion between the states E_3 and E_2 is quickly established. A spontaneous photon of energy $h\nu = E_3 - E_2$ can initiate a chain of stimulated emissions culminating in lasing. The laser transition takes the atoms to the level E_2. From there, the atoms lose the rest of their excess energy by radiative or non-radiative transitions and finally reach the ground state E_1. Atoms are once again available for excitation.

In contrast to three level scheme, the lower laser transition level in four level scheme is not the ground state and is virtually vacant. As soon as some atoms are pumped to the upper laser level, population inversion is achieved. Thus, it requires less pumping energy than does a three level laser. This is the major advantage of this scheme. Further, the lifetime of the lower laser transition level E_2 is much shorter as it is not a metastable state. Hence atoms in level E_2 quickly drop to the ground state. This steady depletion of E_2 level helps sustain the population inversion by avoiding an accumulation of atoms in the lower lasing level. Therefore, four level lasers can operate in a *continuous wave (cw) mode.*

1.33 AMPLIFICATION AND GAIN

When an active medium is in the inverted state, a photon of appropriate energy can stimulate the emission of a cascade of photons. This is the process of amplification. The initial photon may be looked upon as the input signal, the active medium as the quantum optical amplifier and the emerging light as the amplified output. The degree of amplification is measured as gain which is the increase in intensity when a light beam passes through an active medium. The gain may be expressed as

$$G = \frac{1}{I}\cdot\frac{dI}{dx} \qquad \text{...(1.85)}$$

The *gain* may be otherwise defined as the amount of stimulated emission which a photon can generate as it travels a given distance. For example, if $G = 4$ per cm, it means that one photon produces four photons per each centimeter it travels in the medium. Unfortunately, laser materials have a very low gain, of the order of 0.0001/cm to 0.01/cm It means that the photon has to travel a long length of the laser material for producing large amplification. As an example, if we have a material whose gain is 0.001/cm and if we wish to achieve a light amplification of 1000 times, it is calculated that the light has to travel about 69 meters in the medium. Such long distances are obviously not practical. However, the important point to note here is that the amount of amplification increases rapidly with the distance.

In practice, laser materials are not used to amplify light from some outside source. Laser, despite its name, is basically a generator of light.

One of the ways of making light to pass through a long length of laser medium is by keeping mirrors on both sides of a short laser rod or tube. The light bounces back and forth between the mirrors and makes many passes through the medium increasing the effective distance of travel by many times. Such an arrangement of mirrors transforms the simple amplifying medium into a source of light.

Although population inversion is necessary for light amplification, it alone is not sufficient to make the stimulated emissions dominate other processes. According to the relation (1.65), large radiation energy density $\rho(\nu)$ is required to be present in the active medium for this purpose. The pair of mirrors help to maintain a large radiation density in the medium.

1.34 AMPLIFIER

A rod shaped laser medium without end mirrors acts as an amplifier. A light beam of appropriate frequency incident on one end triggers stimulated emission and an amplified output will emerge from the other end. Such amplifiers are used to increase laser pulse powers to higher levels and to amplify weak signals in fiber optic communication systems.

1.35 OPTICAL RESONATOR

Basically a laser is very much similar to an electronic oscillator. In an electronic oscillator, an amplifier tuned to a specific frequency is provided with a positive feedback, as shown in Fig. 1.24. When the oscillator is switched on, any noise signal of the appropriate frequency appearing at the input will be amplified. The amplified output is fed back to the input and is amplified again, and so on. A stable output is quickly reached and the oscillator acts as a source of the particular frequency. In case of low frequency electronic oscillators, the feedback may be given using electric wires. However at high frequencies, waves can not be confined in wires and hence different kinds of feedback mechanisms are to be used. At microwave frequencies, for example, cavities are used.

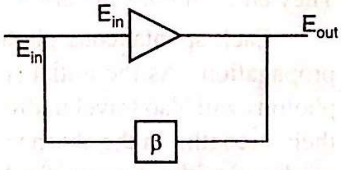

Fig. 1.24 Feedback Oscillator