**Lasers: Fundamentals, Types, and Operations**

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The acronym LASER, constructed from *L*ight*A*mplification by *S*timulated *E*mission

of *R*adiation, has become so common and popular in every day life that it is now

referred to as *laser*. Fundamental theories of lasers, their historical development

from milliwatts to petawatts in terms of power, operation principles, beam characteristics,

and applications of laser have been the subject of several books [1–5].

Introduction of lasers, types of laser systems and their operating principles, methods

of generating extreme ultraviolet/vacuum ultraviolet (EUV/VUV) laser lights,properties of laser radiation, and modification in basic structure of lasers are the main sections of this chapter

The first theoretical foundation of LASER and MASER was given by Einstein

in 1917 using Plank’s law of radiation that was based on probability coefficients

(Einstein coefficients) for absorption and spontaneous and stimulated emission

of electromagnetic radiation. *Theodore Maiman* was the first to demonstrate the

earliest practical laser in 1960 after the reports by several scientists, including the

first theoretical description of *R.W. Ladenburg* on stimulated emission and negative

absorption in 1928 and its experimental demonstration by *W.C. Lamb* and *R.C.*

*Rutherford* in 1947 and the proposal of *Alfred Kastler* on optical pumping in 1950

and its demonstration by *Brossel*, *Kastler*, and *Winter* two years later. *Maiman’s* first

laser was based on optical pumping of synthetic ruby crystal using a flash lamp

that generated pulsed red laser radiation at 694 nm. Iranian scientists *Javan* and

*Bennett* made the first gas laser using a mixture of He and Ne gases in the ratio of

1 : 10 in the 1960. *R. N. Hall* demonstrated the first diode laser made of gallium

arsenide (GaAs) in 1962, which emitted radiation at 850 nm, and later in the same year *Nick Holonyak* developed the first semiconductor visible-light-emitting laser

**Basic Construction and Principle of Lasing**

Basically, every laser system essentially has an active/gain medium, placed between

a pair of optically parallel and highly reflecting mirrors with one of them partially

transmitting, and an energy source to pump activemedium. The gainmedia may be

solid, liquid, or gas and have the property to amplify the amplitude of the light wave

passing through it by stimulated emission, while pumping may be electrical or

optical. The gain medium used to place between pair of mirrors in such a way that

light oscillating between mirrors passes every time through the gain medium and

after attaining considerable amplification emits through the transmitting mirror.

Let us consider an activemedium of atoms having only two energy levels: excited

level *E*2 and ground level *E*1. If atoms in the ground state, *E*1, are excited to the

upper state, *E*2, bymeans of any pumpingmechanism (optical, electrical discharge,

passing current, or electron bombardment), then just after few nanoseconds of

their excitation, atoms return to the ground state emitting photons of energy

*hν* = *E*2 − *E*1. According to *Einstein’s* 1917 theory, emission process may occur in

two different ways, either it may induced by photon or it may occur spontaneously.

The former case is termed as *stimulated emission*, while the latter is known

as *spontaneous emission*. Photons emitted by stimulated emission have the same

frequency, phase, and state of polarization as the stimulating photon; therefore they

add to the wave of stimulating photon on a constructive basis, thereby increasing

its amplitude to make lasing. At thermal equilibrium, the probability of stimulated

emission is much lower than that of spontaneous emission (1 : 1033), therefore

most of the conventional light sources are incoherent, and only lasing is possible

in the conditions other than the thermal equilibrium.

1.1.3

**Einstein Relations and Gain Coefficient**

Consider an assembly of *N*1 and *N*2 atoms per unit volume with energies *E*1

and *E*2(*E*2 *>E*1) is irradiated with photons of density *ρν* = N h*υ*, where [*N*] is the

number of photons of frequency *ν* per unit volume. Then the stimulated absorption

and stimulated emission rates may be written as *N*1*ρvB*12 and *N*2*ρvB*21 respectively,

where *B*12 and *B*21 are constants for up and downward transitions, respectively,

between a given pair of energy levels. Rate of spontaneous transition depends on

the average lifetime, *τ*21, of atoms in the excited state and is given by *N*2*A*21, where

*A*21 is a constant. Constants *B*12, *B*21, and *A*21 are known as *Einstein coefficients*.

Employing the condition of thermal equilibrium in the ensemble, Boltzmann

statistics of atomic distribution, and Planck’s law of blackbody radiation, it is easy

to find out *B*12 = *B*21, *A*21 = *B*21(8*πhν*3*/*c3), known as *Einstein relations*, and ratio,

*R* = exp(*hν/kT*) − 1, of spontaneous and stimulated emissions rates. For example,

if we have to generate light of 632.8nm (*ν* = 4*.*74 × 1014 Hz) wavelength at room

temperature from the system of He–Ne, the ratio of spontaneous and stimulated

emission will be almost 5 × 1026, which shows that for getting strong lasing one has to think apart from the thermal equilibrium. For shorter wavelength, laser,

ratio of spontaneous to stimulated emission is larger, ensuring that it is more

difficult to produce UV light using the principle of stimulated emission compared

to the IR. Producing intense laser beam or amplification of light through stimulated

emission requires higher rate of stimulated emission than spontaneous emission

and self-absorption, which is only possible for *N*2 *>N*1 (as *B*12 = *B*21) even though

*E*2 *>E*1 (opposite to the Boltzmann statistics). It means that one will have to create

the condition of *population inversion* by going beyond the thermal equilibrium to

increase the process of stimulated emission for getting intense laser light.

If a collimated beam of monochromatic light having initial intensity *I*0 passes

through the mentioned active medium, after traveling length *x*, intensity of

the beam is given by *I*(*x*) = *I*0e−*αx*, where *α* is the absorption coefficient of the

medium, which is proportional to the difference of *N*1 and *N*2. In the case of

thermal equilibrium *N*1 \_ *N*2 the irradiance of the beam will decrease with the

length of propagation through the medium. However, in the case of population

inversion, (*N*2 *>N*1) − *α*, will be positive and the irradiance of the beam will

increase exponentially as *I*(*x*) = *I*0e*kx*, where *k* is the gain coefficient of the

medium and may be given by *k* = (*nN*d*hν*21*B*21)*/c*, where *N*d is *N*2−*N*1, *c* is speed

of light, and *n* is refractive index of the medium.

**Multilevel Systems for Attaining Condition of Population Inversion**

Considering the case of two energy level system under optical pumping, we

have already discussed that *B*12 = *B*21, which means that even with very strong

pumping, population distribution in upper and lower levels can only be made equal.

Therefore, optical as well as any other pumping method needs either three or four

level systems to attain population inversion. A three level system (Figure 1.1a)

irradiated by intense light of frequency *ν*02 causes pumping of large number of

atoms from lowest energy level *E*0 to the upper energy level *E*2. Nonradiative decay

of atoms from *E*2 to *E*1 establishes population inversion between *E*1 and *E*0 (i.e.,

*N*1 *>N*0), which is practically possible if and only if atoms stay for longer time in

the state *E*1 (metastable state, i.e., have a long lifetime) and the transition from *E*2 to

*E*1 is rapid. If these conditions are satisfied, population inversion will be achieved

between *E*0 and *E*1, which makes amplification of photons of energy *E*1 − *E*0 by

stimulated emission. Larger width of the *E*2 energy level could make possible

absorption of a wider range of wavelengths tomake pumping more effective, which

causes increase in the rate of stimulated emission. The three level system needs

very high pumping power because lower level involved in the lasing is the ground

state of atom; therefore more than half of the total number of atoms have to be

pumped to the state *E*1 before achieving population inversion and in each of the

cycle, energy used to do this is wasted. The pumping power can be greatly reduced

if the lower level involved in the lasing is not ground state, which requires at least a

four level system (Figure 1.1b). Pumping transfers atoms from ground state to *E*3,

from where they decay rapidly into the metastable state *E*2 to make *N*2 larger than*N*1 to achieve the condition of population inversion between *E*2 and *E*1 at moderate

pumping.

**Optical Resonator**

An optical resonator is an arrangement of optical components, which allows a beam

of light to circulate in a closed path so that it retraces its own path multiple times,

in order to increase the effective length of the media with the aim of large light

amplification analogous to the positive feedback in electronic amplifiers. Combination

of optical resonator with active medium is known as *optical oscillator*. A set

of two parallel and optically flat mirrors, with one highly reflecting M1(*R* ≈ 100%)

and another partially transmitting M2(*R>*95%), makes a simple optical oscillator

as shown in Figure 1.2. Some of the pumped atoms in the excited states undergo

spontaneous emission generating seed photons, which pass through the active

medium and get amplified through stimulated emission. Most of the energy gets

reflected from both the mirrors, passes through the active medium, and continues

to get amplified until steady state level of oscillation is reached. After attaining this

stage, amplification of wave amplitude within the cavity dies away and extra energy

produced by stimulated emission exits as laser output from the window M2. The

gain coefficient inside the cavity should be greater than the threshold gain coefficient

(*k*th) in order to start and maintain laser oscillation inside the cavity. Owing

to the diffraction effects, it is practically difficult to maintain a perfectly collimated

beam with the combination of two parallel plane mirrors, which causes significant

amount of diffraction losses. Such losses could be reduced by using a combination

of concave mirrors and other optics in different optical arrangements. The optical

configurations, which are able to retain the light wave inside the cavity after several

transversals, are known as *stable resonators*. Some of the stable resonators are shown

in the Figure 1.3. Laser oscillators with different geometries have their own benefits

and losses. For example, in an oscillator having assembly of two parallel mirrors,

it is difficult to align them in a strictly parallel manner. A slight deviation from the

parallel geometry of the laser beam causes its walk away from the cavity axis after

few reflections. However, it is beneficial in the sense that a large fraction of the

active medium (mode volume) is pumped in this geometry. Confocal resonators are

very simple to align, although lesser fraction of the activemedium is being pumped.

Every laser resonator is characterized by a quantity *Q* termed as *quality factor*,

which is defined by *Q* = (2*π* × energy stored)*/*(energy dissipated per cycle). The

*Q* value of laser cavities lies in the range of ∼105−106. Significance of higher *Q*

value lies in the sense of capacity to store larger energy. In terms of line width *ν*, Basic geometry of laser cavity: (1) 100% and (2) 95–98% reflecting mirrors, (3)

active medium, (4) pumping source, and (5) laser output.