Chapter 4
Lasers: At a Glance

4.1 Introduction

The discrete nature of energy levels and the transition of atoms from excited to lower levels are, as we know now, the origin of quantum light sources that we so commonly make use of for illumination and eye-catching displays at night. Quantum sources of light are also employed in the laboratory for many light-based experiments. Instances are aplenty when the outcome of such experiments has compelled the enigmatic nature to unwillingly unravel some of its deepest secrets. For instance, an explanation of the photoelectric effect, discovered in the beginning of the last century when ultraviolet light was made to shine on a metal surface, as perceived by Albert Einstein, cemented the photonic concept of light. Incidentally, as the majority of readers are perhaps aware of, Einstein was awarded the Nobel Prize in Physics for unmasking the physics underneath the photoelectric effect and not for his earthshaking work on relativity. It is also well known that Chandrashekhar V. Raman (1888–1970) made use of a mercury vapor lamp in his experiments when he showed that upon scattering from an appropriate medium, the photon energy can either increase or decrease, a discovery that fetched him a Nobel Prize in physics. We shall take a closer look at his ingenious experiment in a future chapter (V-II). Just as it occurs in such light sources, in a laser too, a transition of an excited species to a lower energy level is the basis of light emission. However, what makes the laser so distinctly different from this other kind of sources? To unravel this, we need to first understand the working of a common quantum source of light. The purpose of this chapter is to further this understanding toward imparting a rudimentary impression of the laser into the mind of the readers without compromising the scientific accuracy. The anecdote picked from the history enveloping the invention of laser by Maiman[1] provides a seamless ending to this

[1] Interested readers may refer in this context to the book *The Laser Odyssey* by Theodore Maiman, creator of the world's first laser.

D. J. Biswas, *A Beginner's Guide to Lasers and Their Applications, Part 1*,
Undergraduate Lecture Notes in Physics,
https://doi.org/10.1007/978-3-031-24330-1_4

stand-alone chapter. Subsequent chapters (5 to 12) of this part of the book are devoted to unveiling the laser more comprehensively while preserving the intuitive approach of this endeavor.

4.2 Working of a Conventional Fluorescent Light

A typical fluorescent tube light that illuminates our surroundings in the dark is schematically illustrated in Fig. 4.1. A glass discharge tube here contains some neutral atomic gaseous species that we call *A* at a low pressure, typically, a few

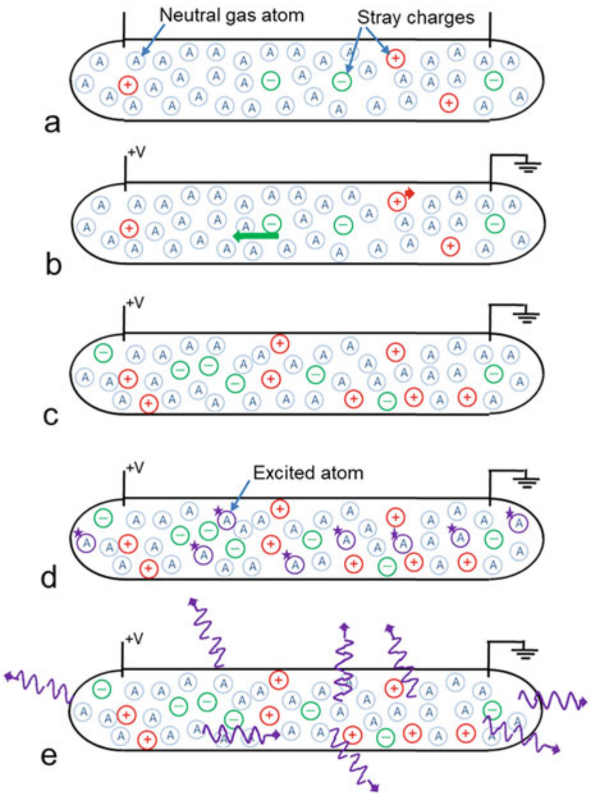

Fig. 4.1 Schematic representation of the mechanism of operation of a conventional fluorescent light source (**a**) The glass discharge tube containing the neutral gas atoms and a few stray electrons and ions (**b**) On application of voltage V, the charges are accelerated. Electron, being much lighter, is accelerated faster acquiring higher kinetic energy (**c**) The accelerated electrons with appropriate KE on collisions with neutral atoms result in their ionization creating an avalanche of electrons (**d**) Some of the collisions of the electrons with neutral atoms may be inelastic wherein the atom gets electronically excited (**e**) The excited atoms return to the ground state releasing the excitation energy in the form of photons emitted randomly

torr or so. Although electrically neutral, the presence of at least a few stray charges in the form of electrons and cations in the gas, however small, is inevitable[2] (Fig. 4.1a). Upon application of an appropriate voltage *V* across the two electrodes placed at the two ends of this tube and separated by a distance *d*, both the electrons and the positive charges experience a force that results in their acceleration, the electrons toward the anode and the positive ions toward the cathode (Fig. 4.1b). The electrons being much lighter experience significantly higher acceleration given by eE/m_e, where $E = V/d$ is the applied electric field, m_e is the mass of the electron, and e is the charge on it. As the electron moves, it gains velocity and thus acquires kinetic energy. If the electron, after acquiring sufficiently high kinetic energy, collides with a neutral atom *A*, it may then succeed in its ionization, leading to the creation of an additional electron that, in turn, participates in the process of further ionization (Fig. 4.1c). This avalanche effect results in a copious supply of electrons leading to the flow of current. The ions, being massive compared to the electrons, have negligible contributions to the flow of current. Some of the collisions of the electrons with the neutral atoms can also be inelastic. This means that a part of the kinetic energy of the electron is transferred to the atom as its internal energy, and the atom, in turn, is electronically excited (Fig. 4.1d). The excited atom decays to the lower energy state after a finite time releasing this energy of excitation as a quantum of light, the so-called photon. Since these are random emissions, the resulting photons would travel in all possible directions around the discharge tube, i.e., over the entire 4π solid angle around it (Fig. 4.1e). The light from this device would, therefore, spread everywhere and hence is most suitable for the purpose of viewing. In practice, conventional tube lights contain mercury vapor, and the walls are coated with fluorescent paint to absorb the photons emitted in the discharge and reemit in the visible region.

4.2.1 Is It Possible to Force an Excited Atom to Emit Photon in a Particular Direction?

An obvious question that arises here is if it would be possible to force all the electronically excited atoms in "Fig. 1d" to emit in the same direction, say along the axis of the discharge tube. If it indeed happens, it is not difficult to imagine that the beam of light that now emerges would be enormously more intense (Fig. 4.2). The answer to this question is an emphatic *yes*, thanks to the deep insight of Albert Einstein, who envisaged the possibility of stimulated emission way back in 1917. However, it took more than four decades for the experimental exploitation of stimulated emission to manufacture such a unique beam of light. The name Einstein is synonymous with $E = mc^2$ or the *theory of relativity* and may be to some extent

[2] Cosmic radiation that reaches the Earth surface from the outer space is responsible for the presence of charged particles in our atmosphere.

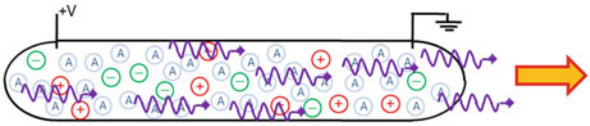

Fig. 4.2 If all the excited atoms of Fig. 1d were to emit in a particular direction, a powerful beam of light would then emerge. The device, however, ceases to remain a viewing source anymore

with the explanation of the photoelectric effect that an informed reader might associate with his Nobel Prize winning piece of work. However, it is much less well known that the innovative concept of stimulated emission, which has given birth to a device that now has practically pervaded every walk of our life, is also his brainchild. Before venturing into the realization of stimulated emission in an experimental system, it would be useful to briefly describe the spontaneous and stimulated emission processes.

4.3 Spontaneous and Stimulated Emissions

Let us consider an atom in an excited electronic state. This energy of excitation can be imparted by shining it with a photon of just the right amount of energy or through an inelastic collision with an electron possessing an appropriate amount of kinetic energy, as is the case of a fluorescent light source. After spending a finite amount of time in the excited state, the atom eventually comes down to the ground state, releasing this energy of excitation as a photon. The photon can be emitted anywhere within the entire 4π solid angle around this excited atom. Such an emission, which makes it possible for a viewing source to spread its light everywhere, is called spontaneous or random emission, and the same is qualitatively depicted in Fig. 4.3. Let us once again consider an atom in the excited state that is in the verge of spontaneously emitting a photon of frequency ν. However, in the event of its interacting with a photon (I) of the same frequency ν, while it is still in the state of excitation, it would instantaneously come down to the ground state, emitting a second photon (II). Furthermore, this second photon is identical to the first photon (I), which interacts with the excited atom, called the stimulating photon, in all respects. Most importantly, it travels in the same direction as the first photon. Such an emission is called forced, induced, or stimulated emission and is schematically depicted in Fig. 4.4. It is obvious from this discussion that the seed for stimulated emission is spontaneous emission itself.

Returning to the example of tube light, the photons due to spontaneous emission will be emitted by the excited atoms in all possible directions. However, the photons that happen to travel along the axis of the tube light will have the opportunity to stimulate the maximum number of excited atoms to emit identical photons along the same direction. This is not the end of the story. All these photons emitted due to stimulated emission, traveling along the axis by default, will cause further

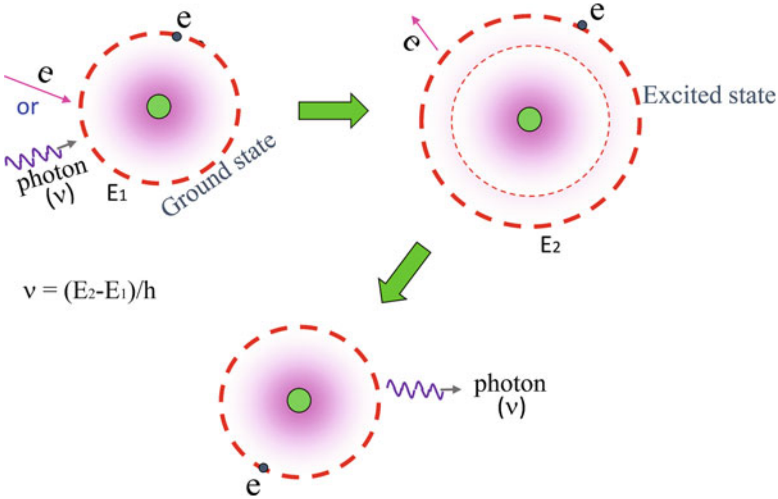

Fig. 4.3 Schematic representation of spontaneous emission. An atom having absorbed a photon of appropriate frequency or inelastically scattered by an electron goes into the excited state. After a finite residence time, the excited atom returns to the ground state releasing the excitation as a photon

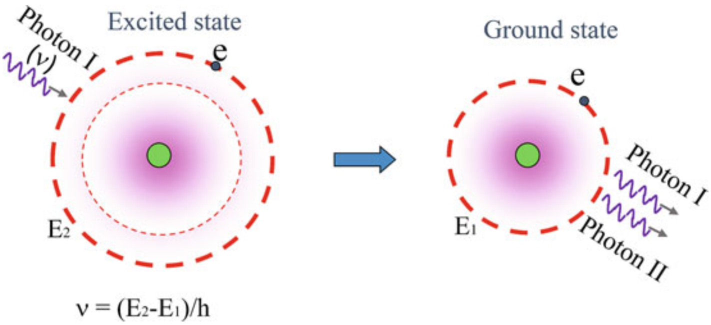

Fig. 4.4 Schematic representation of stimulated emission. The atom may reach the excited state in the same way as depicted in Fig. 4.3. When a photon of appropriate energy interacts with this excited atom, it instantly comes down to the ground state emitting a photon that is identical in all respect to the photon that caused this de-excitation

stimulation of excited atoms on their path, leading to a multifold rise in their number. Thus, ordinary tube light should also be able to give an intense beam of light as a result of amplification of those few spontaneously emitted photons along the tube axis. Surely this is not true; otherwise, the laser would have come into existence more than a century ago along with large discharge length tube lights. Where then lies the fallacy??

4.4 Population Inversion and Amplification of Light

Let us consider the simple case of an ensemble of atoms that are capable of residing either in the lower or excited energy states (Fig. 4.5). Under normal conditions, the majority of the atoms occupy the lower energy state, as depicted in Fig. 4.5a, following the Boltzmann distribution, we studied in the preceding chapter. We shine this medium by a beam of light comprising photons of energy $h\nu$ that exactly matches the difference in energy between these two levels, called resonant photons. As these photons travel through the medium, they may interact with the population both in the lower or excited energy levels. If a photon interacts with an atom in the lower state, it is absorbed, and the atom in turn is excited. On the other hand, if it interacts with an excited atom, it stimulates it to return to the lower state emitting in the process a second photon, identical to the first, the so-called stimulated emission. However, as the number of atoms in the lower state is greater than that in the excited state, the absorption of photons will exceed the number of photons emitted due to

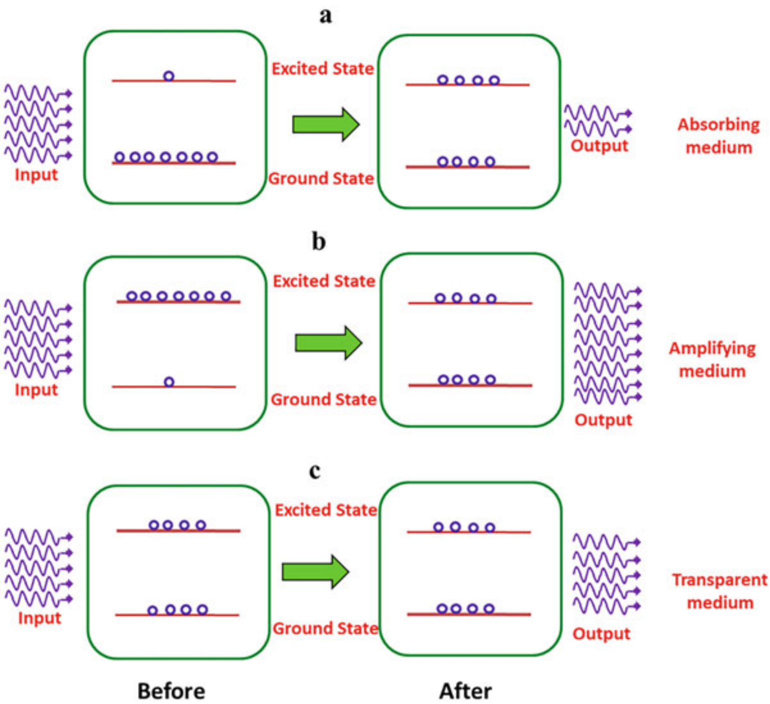

Fig. 4.5 Schematic illustration of the passage of a beam of light through a resonant medium (**a**) Normal case where majority of population resides in the ground state. Understandably, the medium behaves here like an absorber (**b**) A special case where population in the excited level exceeds the ground state population. The medium here is conducive for amplification of light by stimulated emission (**c**) Another special case when the population of the excited and ground states are equal. The medium here behaves like a transparent window

stimulated emission. Thus, the incident beam, as it traverses through the medium, is gradually diminished in the number of photons, and an attenuated beam finally emerges (Fig. 4.5a). The medium therefore behaves as an absorber here. At this point, we consider the reverse situation wherein the population in the excited level exceeds that in the lower level (Fig. 4.5b). The traversing beam in this case interacts more with the atoms in the excited state than with those in the lower state, causing the stimulated emission to outnumber the absorption. The net effect would therefore be amplification of the input beam (Fig. 4.5b). Thus, we see that amplification of light by stimulated emission of radiation would be possible if and only if the population of the excited energy level exceeds that of the lower level, a condition that is normally termed population inversion. However, such a situation violates the Boltzmann equilibrium and thus cannot come about naturally. In reality, therefore, the population in the excited level is always lower than that in the lower level unless a mechanism to invert the population,[3] a trick not so easy to realize, is in place. In an ordinary fluorescent tube light, although the electric discharge succeeds in transferring a fraction of the ground state population to the excited state, the condition of population inversion is not met. The amplification of light by stimulated emission is thus ruled out, resulting in the predominance of spontaneous emission spreading the light in all directions. It would be pertinent here to consider a third situation, as represented in Fig. 4.5c, where the population of the two levels is equal. The chance of the photons of the incident beam interacting with the population in the two levels being the same, it is understandable that the incident light beam now traverses through the medium unaffected. The medium now behaves like a transparent window. This situation, like the case of population inversion, is also a violation of the Boltzmann distribution, and the ways of experimentally realizing a population inverted condition will be addressed in the following chapter.

Thus, a light amplifier can be pictured much the same way as Fig. 5b, where there is a medium in which the population is inverted between two energy levels and an input beam of identical resonant photons of energy matching exactly with the energy difference of these two levels passes through it. The medium, by virtue of stimulated emission, adds more identical photons to this incident group of photons and, in turn, gives out an amplified beam of light. The higher the population inversion is, the greater the amplification. Thus, we can say that the gain of this optical amplifier increases with increasing population inversion. Laser, we now know, is the acronym for light amplification by stimulated emission of radiation. Therefore, it is also an amplifier of light but surely does not require an input source for its operation. If it did, then the laser would have lost all its charm. How does it work then? It amplifies light and yet it does not need an input for amplification! To understand this, we must know what a cavity is.

[3] This can be achieved if somehow the population is selectively transferred from the source to the excited level.

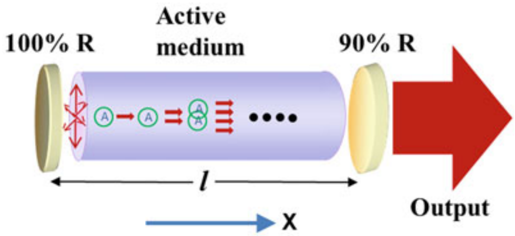

Fig. 4.6 Schematic representation of the multiplication of photons due to stimulated emission, initiated by the emission from a single excited atom inside a simple cavity. The black dots represent continuation of the same process

4.5 A Simple Cavity

A simple cavity is formed when two high reflectivity mirrors are placed parallel to each other at a given separation. Here, we consider one of the mirrors to have 100% reflectivity, while the other is 90% reflective, meaning that it has a transmission of 10%. The population inverted medium, also called an active medium, is placed inside this cavity (Fig. 4.6). The excited atoms spontaneously decay to the ground state, emitting photons in all directions, as shown in the figure. In this figure, we have tagged one such atom *A*, at the extreme left end, that happens to have emitted a photon along the axis of the cavity in the positive X direction. As it travels, the photon encounters another excited atom *A* and stimulates it to emit an identical photon. Thus, we have two identical photons traveling along the cavity axis that are ready to cause two more stimulations, making the number of identical photons moving along the axis four. This process continues taking the number of identical photons to astronomical values.[4] This happens only because the number of excited atoms exceeds their number in the ground state in an active medium. The point that needs to be emphasized here is that while we have considered only a single excited atom at one end of the medium, this holds true for innumerable excited atoms lying anywhere in the active medium and emitting axially. It is also not difficult to visualize that the same story holds true for every excited atom emitting photon in the negative X direction. The photons traveling in the –X direction are reflected off the 100% R mirror; travel through the inverted medium again, causing further multiplication of their number; and reach the partially reflecting (90% R) mirror where the majority of them are reflected back. The back-and-forth oscillation of these photons and their repeated passage through the inverted medium culminate in the generation of a huge photon flux inside the cavity, a part of which continues to be emitted through the partially transmitting mirror as the laser output. The spontaneous emission in any direction other than the axis (as depicted in Fig. 4.6) cannot grow in

[4] The increase in the number of photons is exponential and is proportional to e^{gl} where gain g is directly proportional to population inversion and l is the length of the active medium.

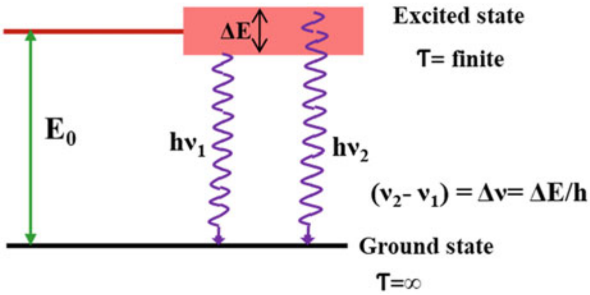

Fig. 4.7 Finite lifetime associated with an excited energy state leads to its broadening in energy in accordance with Heisenberg's uncertainty principle. The residence time in the ground state being infinite has no such broadening. The energy broadening leads to a corresponding spread in the transition frequencies

this manner due to the absence of a cavity.[5] It is easy to understand that to obtain a continuous beam of light from this device, the mechanism for creating population inversion, also called "pumping," must also be operational in a continuous manner (readers are referred to Chap. 7 for more comprehensive knowledge on this). Obviously, therefore, a laser does not require an input source of light for its operation. The cavity enables the spontaneously emitted photons to perform the role of input seed photons for amplification through stimulated emission.

It is well known that an atom has a finite residence time in the excited state before it decays spontaneously to the ground state (readers may also refer to Chap. 8 in this context). Invoking Heisenberg's uncertainty principle once again but now with respect to canonically conjugate variables,[6] time and energy, it is straightforward to show that the finite residence time leads to a corresponding spread in the values of energy that the excited atom can possess, aptly termed the broadening of the energy levels. This situation has been illustrated in Fig. 4.7. This spread in energy of the excited state will result in a corresponding spread in the frequency of the spontaneously emitted photons. Since the stimulated emission is seeded by these spontaneous photons, one would also expect a similar frequency spread in the emission of the laser. If true, then the color of the laser light would be far from pure. The cavity does not allow this to happen, as it lets to and fro oscillations only for those wavelengths, half of which times an integer fits exactly inside it. These discrete wavelengths or corresponding frequencies are called cavity modes and have been elaborated in greater detail in Chap. 6. The cavity, by virtue of its discretionary power, would allow only those photons to grow through stimulated emission whose frequency matches that of the cavity modes and thus helps the laser to preserve the purity of its color. Unquestionably, therefore, the integration of a cavity with stimulated emission

[5] The amplification in certain cases can be extremely high in a single pass itself. This is called amplified spontaneous emission.

[6] If the product of dimension of any two variables equals the dimension of the Planck's constant h, then they are called canonically conjugate variables in the present context.

not only allows multi-pass amplification but also makes its emission both directional and monochromatic. Thus, we have now zeroed in on the two most important characteristics of lasers, viz., monochromaticity and directionality, which, in turn, lead to many other attributes that a laser is associated with as elucidated in Chap. 6. However, the very first laser that Theodore Maiman operated in 1960 did not make use of a conventional cavity.[7] One would then begin to wonder as to how amplification of light by stimulated emission manifested in his device. It would be interesting to digress a little here to know the story behind the first experimental demonstration of light amplification by stimulated emission of radiation.

4.6 Maiman's Experiment: Invention of Laser

American physicist Theodore Maiman operated the first laser, a ruby laser, on May 16, 1960, at the Hughes Research Laboratories in Culver City, California. As a tribute to this magnificent invention, May 16 is celebrated as International Day of Light all over the world. The paper that Maiman wrote to report this invention comprised just a few illustrations and a small text. It appears that there was an element of urgency to quickly disseminate his results. This is understandable considering the intense research activity that was being witnessed at that time aimed at achieving the first experimental demonstration of amplification of light by stimulated emission of radiation. It is also possible that Maiman, having obtained the results, was confident that they stood tall enough to prove the point that he was making. The paper in its rudimentary form was communicated to *Physical Review Letters (PRL)* for consideration for publication. The then-editor Sam Goudsmit misjudged the value of the work and found it to be unsuitable to warrant publication in a journal of the repute of *PRL*. This paper of Maiman was then subsequently published in the prestigious *British Journal Nature*, which has since been recognized as the first ever experimental demonstration of amplification of light by stimulated emission of radiation. It may be of interest to note here that even after submitting the paper to *Nature*, Maiman appealed to the editor of *PRL* to reconsider his decision and offered to withdraw the paper from *Nature* if he would agree to its publication. Goudsmit, however, refused to budge and, worst still, labeled this revolutionary piece of work as duplicate. In 2003, *Nature* brought out a unique book entitled *A Century of Nature: Twenty-One Discoveries That Changed Science and the World*, wherein the invention of lasers written by Charles H. Townes, a recipient of Nobel Prize for his overall contribution in the development of the coherent source of EM radiation, featured as the eighth article. In Townes' own word, "the Maiman's paper

[7] Although this fact was not explicitly mentioned by Maiman in the paper he wrote reporting the invention of the laser, the non-emergence of a beam of light points to the cavity less operation of the very first laser. This aspect was also corroborated by Nobel Laureate Charles Townes in his article "The First laser" in *A Century of Nature: Twenty-One Discoveries That Changed Science and the World* Nature, 2003, Ed: Laura Garwin and Tim Lincoln.

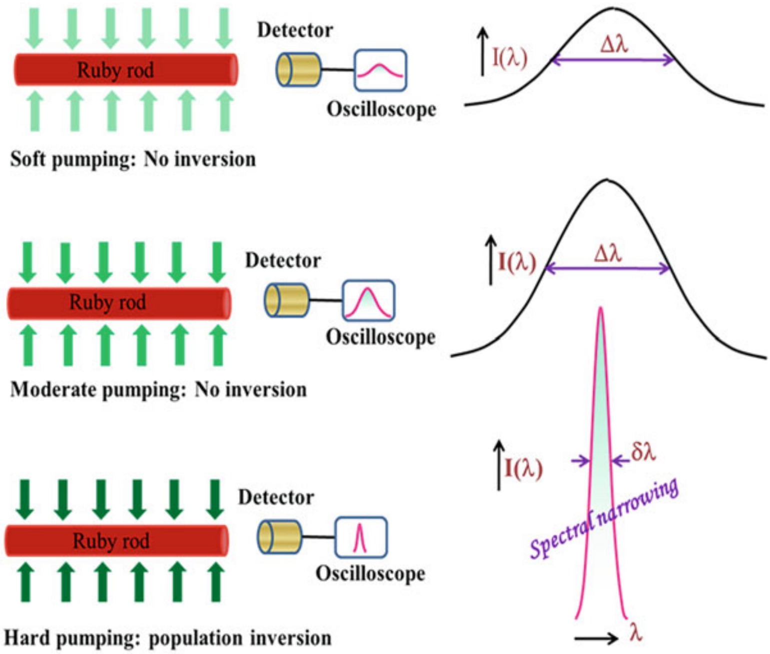

Fig. 4.8 A cylindrical ruby rod is optically pumped by a flashlamp, and the resulting fluorescence is monitored by an appropriate detector placed on one end of the ruby. At low flashlamp intensity, the spectral width of the emission matched with the known fluorescence width of ruby (top trace). At a moderate flashlamp intensity, the fluorescent intensity too increased but its spectral width was the same (middle trace). At high flashlamp intensity that caused population inversion, the significant spectral narrowing of the fluorescence provided the first ever signature of amplification of light by stimulated emission of radiation (bottom trace)

is so short and has so many powerful ramifications that I believe it might be considered the most important per word of any of the wonderful papers in Nature over the past century." This ornate observation coming from a noble laureate who himself was outdone by Maiman in the race to create the very first laser speaks volumes of the importance of this work.

Here, we present an easy-to-understand explanation of Maiman's work[8] by using an overtly simplified illustration as depicted in Fig. 4.8. A cylindrical ruby rod was optically pumped by deriving light from a flashlamp. A part of the light emitted by the flashlamp can cause resonant electronic excitation of the ruby molecule that would subsequently fluoresce light of a correspondingly longer wavelength. The

[8]The text and illustrations here are not a reproduction from Maiman's original research paper. To make it palatable to the readers, illustrations have been redrawn and accompanied by suitable explanation to elucidate the central theme of his work. Interested readers are referred to his original paper [T. H. Maiman, Nature 187: 493–494, August 6, 1960] to know about the invention of laser in the inventor's own words.

fluorescence has a spectral width for the same reason for which the gain has a spectral broadening, the so called Heisenberg's uncertainty principle, as elaborated earlier in this chapter. Maiman attempted to study the fluorescence as a function of its wavelength by placing an appropriate detector at one end of the ruby rod. This was done for three cases of pumping. In the first case, the intensity of the flashlamp was low, meaning that the pumping was soft. The spectral width $\Delta\lambda$ of fluorescence in this case matched the known fluorescence width (which basically is the spontaneous emission width) of a ruby crystal (Fig. 4.8, top trace). He then increased the intensity of pumping to a moderate level, thereby increasing the number density of the excited species but not good enough to create population inversion. Although the intensity of the fluorescence increased now in accordance with increased pumping, the spectral width of the fluorescence remained invariant (Fig. 4.8, middle trace). In the third case, he increased the intensity of pumping to such an extent that population inversion was created over the length of the ruby rod. In this case, Maiman observed a dramatic narrowing of the spectral width of fluorescence (Fig. 4.8, bottom trace), and he recognized this as a signature of amplification of light by stimulated emission of radiation. We provide below a qualitative explanation of the narrowing of the spectral width of fluorescence as a result of the amplification of light due to the stimulated emission of radiation.

4.7 Spectral Narrowing: A Signature of *Laser*

From the very nature of stimulated emission, it is apparent that its probability at any given frequency increases with increasing number of photons at that frequency. To understand the consequence of this, we imagine the ruby rod to be divided along its length into a number of subsections (Fig. 4.9). First, just for the sake of convenience, let us pick up such a section at the extreme left end. The distribution of photons emitted due to spontaneous emission (fluorescence) across this section with a spectral width of $\Delta\nu$ is shown immediately above it in the figure. A fraction of these photons, moving along the axis to the right, interacts with the inverted medium of the next section, resulting in their amplification. At the central frequency of the fluorescence, called the line center, where the number of photons is the highest, the amplification due to stimulated emission is also the largest. This means that the number of photons at the line center increases more rapidly than at the wings, leading to a narrowing of the spectral width. This continues as the photon distribution propagates through the sections one after the other with the narrowing effect becoming progressively more prominent as is clearly depicted in Fig. 4.9. It should be noted here that the spectral narrowing $\delta\lambda$ shown in this example is the maximum possible as the seed spontaneous photons have begun their journey from the extreme left end, traveling through the entire length of the active medium. This narrowing is thus indeed a clear signature of amplification of light by stimulated emission of radiation. In the two cases of soft and moderate pumping, in the absence of

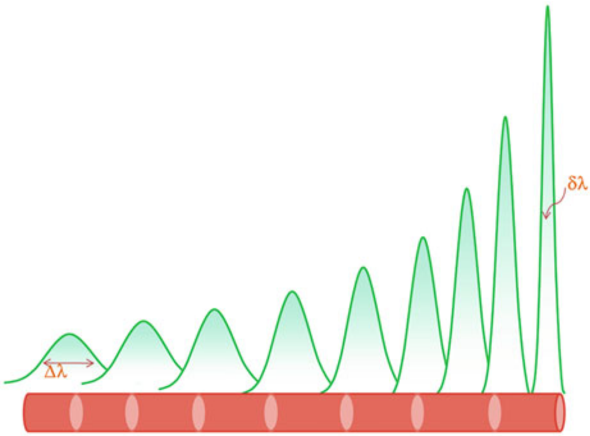

Fig. 4.9 The gradual reduction in spectral width and increase in intensity of the packet of spontaneously emitted photons over a subsection of the active medium as it traverses from extreme left to right through the length of ruby rod wherein population inversion has been created is depicted. Although a single packet of spontaneously emitted photons in the extreme left end of the ruby rod has been considered here, similar sequence of events should occur to the group of photons originating anywhere in the active medium. This decides the overall narrowing of the spectral width

population inversion, the medium acted as an absorber with no effect on the spectral width of fluorescence.

We have used very simple but revealing illustrations to bring out the central role that the population inversion and a cavity play in the operation of a laser. In the following chapters, we shall study the population inversion and cavity and their related effects in greater detail. We also have seen that the spectral narrowing effect bears a distinct signature of the amplification of light by stimulated emission of radiation. While Maiman demonstrated amplification of light by stimulated emission in an active medium without the usage of a conventional cavity, placing it inside a cavity can dramatically improve the monochromaticity of the laser. The spectral narrowing effect becomes much more pronounced in a cavity that in turn leads to much purer color from the laser, as we shall see in a future chapter.