Script “Fundamentals of Laser Physics” - Chapter 1

1. Introduction

Many subareas of Physics investigate objects and phenomena found in Nature, e.g. in solid-state Physics. In contrast, laser Physics deals with a technical device: the LASER. LASER is an artificial word, i.e. an acronym, and stands for “*Light Amplification by Stimulated Emission of Radiation*”.

On a very introductory level a laser is a light source with very unique properties of the emitted radiation. This is, in part, because the light generation is based on a quantum-mechanical process known as “*stimulated emission*”.

In general laser radiation is characterized by:
- high coherence
- good monochromaticity, i.e. narrow linewidth
- low divergence, i.e. the energy can be accurately directed to a target

In addition, lasers are able to generate:
- high optical average powers (>100 kW)
- high peak intensities (>10^{23} W/cm^2)
- ultrashort light pulses (with durations in the order of femtoseconds: 10^{-15} s)

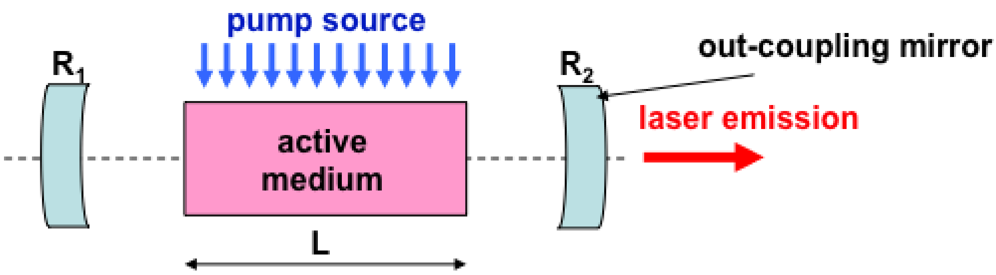
In summary: *a LASER is an intense coherent light source*.

The goal of the lecture is to understand why a laser creates light with such outstanding properties and which applications can be driven by lasers.

Schematic setup of a laser

In principle, each laser consists of 3 main components.

1) *The active medium*. The active medium is the place where amplification happens and it can exist in different states of aggregation (e.g. solid, gaseous, …)
2) *The pump source*. The pump source represents the energy supply for the amplification process. Pumping can be, for instance, electrical or optical.
3) *The resonator / cavity*. The resonator feeds part of the generated / amplified radiation back to the active medium and it is essential for obtaining the above-mentioned properties of the emitted radiation.



$R_{1,2}$: reflectivity of mirror 1 and mirror 2
L: length of the active medium

Simple considerations / threshold condition

Electro-magnetic radiation gets attenuated while propagating through a medium. The well-known Lambert-Beer's law of absorption describes this behavior:

$$I(x) = I_0 \cdot \exp(-\alpha \cdot x) \tag{1.1}$$

In the expression above, the different parameters are:

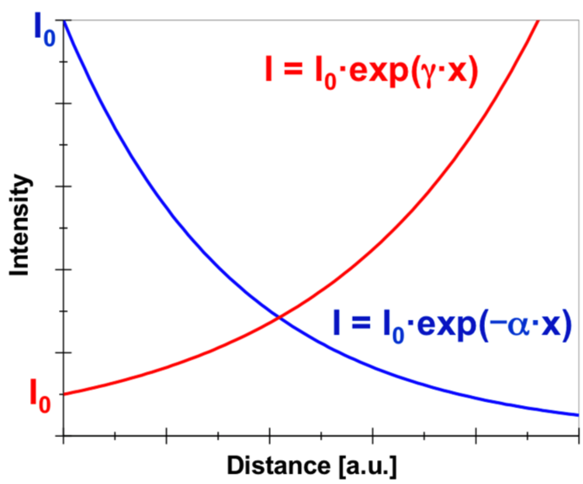
$I(x)$: intensity at position x in in the medium
I_0: input intensity
α: absorption coefficient
x: distance in medium

In an equivalent way, we can describe the growing intensity caused by amplification through stimulated emission in the active medium (without the need to know what stimulated emission is at the moment):

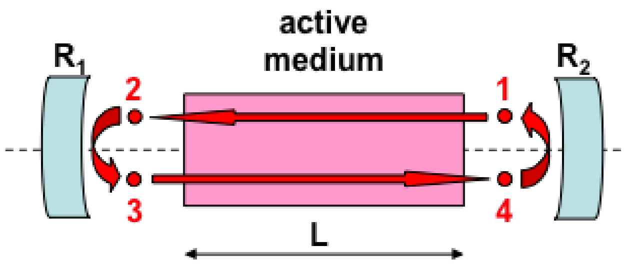
$$I(x) = I_0 \cdot \exp(\gamma \cdot x) \tag{1.2}$$

γ: gain coefficient

Both equations can be illustrated as follows:



In order to gain a deeper insight into what happens in a laser, we consider one round-trip of the light within the resonator (this will be described by tracking the power evolution at 4 positions in the resonator):



A simple power-balance consideration, based on tracking the change of intensity or power as the light propagates from one position to the next, is carried out for this study:

point 1	1 -> 2	2 -> 3	3 -> 4	4 ->1
I_0	$\exp(\gamma \cdot L)$	R_1	$\exp(\gamma \cdot L)$	R_2

By multiplying all the terms in the table above it is possible to obtain the remaining intensity/power after the light has completed one round-trip in the resonator (e.g. when it is again at position 1):

$$I = I_0 \cdot R_1 \cdot R_2 \cdot \exp(2 \cdot \gamma \cdot L) \tag{1.3}$$

If the result of expression (1.3) is larger than the originally existing intensity I_0 (i.e. before the round-trip) at position 1, a positive balance is given, i.e. light gets amplified in the resonator. In other words, the amplification is large enough to compensate for the propagation losses experienced by the light during one round-trip. Take into account, however, that, at the moment, only out-coupling losses (R_1, $R_2 < 1$) have been considered. This simple consideration leads to a first important equation, the laser threshold condition: *"The gain in the active medium has to be bigger than the round-trip propagation losses"*:

$$R_1 \cdot R_2 \cdot \exp(2 \cdot \gamma \cdot L) > 1 \quad \Leftrightarrow \quad \gamma > \frac{1}{2L} \cdot \ln\left(\frac{1}{R_1 \cdot R_2}\right) \tag{1.4}$$

Historic Overview

A very brief overview on the developments which finally led to the realization of the first laser will be provided in the following. A more comprehensive account can be found in the literature.

1927 Albert Einstein
"On the Quantum Theory of Radiation"
Einstein published a re-derivation of Planck's law of radiation based on the concept of probability coefficients (later known as Einstein coefficients). He postulated the stimulated emission of light which, as we know today, is the quantum-mechanical event that lasers are based on.

1928 Rudolph Ladenburg
He succeeded in experimentally confirming the existence of stimulated emission in gas discharges.

1951 Valentin Fabrikant
Published a proposal to amplify electro-magnetic radiation in a medium by means of a supporting radiation, which created a predominant population in higher energy levels.

1952 Charles Townes
Worked with his team on the MASER concept "microwave amplification by stimulated emission of radiation" …

1954	Charles Townes … and succeeded in building the first working MASER in ammonia molecules.
1954	N.G. Basov and A.M. Prokhorov At the same time as Townes, the two Russian scientists Nikolai Basov and Alexander Prokhorov published their proposals and calculations on microwave oscillators based on stimulated emission. In their work a multilevel pumping was added to create population inversion. This is a concept which became a very important recipe for lasers and which has enabled the realization of the first continuous-wave emitting MASER.
1958	A.L. Schawlow and Ch. H. Townes Schawlow and Townes could theoretically show that the functional principle of a MASER can be adapted to the VIS and the IR, i.e. to optical wavelengths.
1959	Gordon Gould Applied for a US patent on the laser device and applications thereof, among them spectroscopy, radar and the ignition of nuclear fusion. He was also the first who used the acronym LASER in his notes.
1960 (June)	Theodore H. Maiman The team around Theodore Maiman was the first ever to develop a working LASER (pulsed). A ruby rod served as the active medium, its mirrored end facets formed the cavity and a pulsed flash lamp was the pump source (optical excitation).
1960 (Dec.)	Ali Javan 6 months after the Ruby laser of Maiman the first continuously emitting LASER was demonstrated. A helium-neon gas mixture was employed as the active medium, with neon as the emitting atom (HeNe laser), and collision excitation in a discharge tube serving as the pump mechanism.

Lasers have historically allowed and still allow for the development of completely new approaches in science. Hence, they are widely regarded as an enabling technology. Furthermore, a considerable market has been developed for lasers and related products over the recent 60 years.