Margherita Zavelani-Rossi – Federico Vismarra

HIGH INTENSITY LASERS
for Nuclear and Physical Applications

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To Mauro
Matilde and Kim
M.Z.R.

To Marta
F.V.

Preface

The first research paper describing the principle of light amplification by stimulated emission of radiation was published in 1958 by A.L. Schawlow and C.T. Townes and the first experimental demonstration was reported in 1960 by. T.H. Maiman. This device was then called *laser* and the idea was awarded by a Nobel Prize in Physics in 1964. The field of laser physics and its applications grew rapidly after the first demonstration; it revolutionized many areas of science and society, providing bright and versatile light sources with unique properties such as coherence, directionality, monochromaticity and intensity.

Nowadays a second laser revolution is underway, with the development of petawatt-class lasers ($1\ PW = 10^{15}\ W$), delivering nearly 100 times the total world's power concentrated into a pulse that lasts less than $1\ ps$ ($1\ ps = 10^{-12}\ s$). Focusing of these high-energy ultra-short pulses leads to *high intensity lasers*. Such achievements are the result of two main technological advances: the production of repetitive trains of short laser pulses, by Q-switching and mode-locking techniques, and their huge amplification, which could be obtained only after the invention of the chirped pulse amplification (CPA) technique in 1985 by G. Mourou and D. Strickland, that was awarded with the Nobel Prize in Physics in 2018. Amplification from nanojoule to kilojoule levels was demonstrated, i.e. a twelve-orders of magnitude increase in energy per pulse. Focused intensity levels exceeding $10^{21}\ W/cm^2$ are currently available and $10^{23}\ W/cm^2$ are anticipated.

Several areas of research benefit of high intensity short laser pulses. No fewer than 50 petawatt-class lasers worldwide are either currently operational, under construction or in the planning phase. One petawatt is no longer the upper limit and the increasing peak-power levels will open new fields of research. Light is is an extraordinary and powerful probe probe to unravel the mysteries of nature. Electromagnetic fields in the focus of a high power laser pulse exert forces that are stronger than chemical forces holding molecules and solids together, stronger than the Coulomb fields that bind electrons in atoms. High-field physics could open windows to new extreme states of matter and it is also of fundamental importance for research in the framework of laboratory astrophysics and inertial confinement fusion.

The technological advances in the field of high intensity lasers led to a widespread availability of high-power, ultra-short pulse systems with high repetition rate. Nowadays, affordable tabletop lasers, that fit university groups' budgets, are used for new research areas such as strong-field physics, attosecond science, and laser-plasma acceleration. It also led to the construction of compact and user-friendly, high-power, ultra-short laser systems, suitable for broad industrial and medical applications, and the innumerable areas of applications have not yet been completely explored.

The aim of this book is to present the main characteristics of high intensity short laser pulses, and a few applications. In particular, we discuss the issues and the challenges related to the production and propagation of this particular kind of pulses. We focus our attention on the physical aspects, together with the technological solutions. We then present relevant applications in the physical and nuclear fields, namely high-order harmonic generation for attosecond science, laser-driven particle acceleration, and laser-driven inertial confinement fusion.

The book originates from a graduate course of the Politecnico di Milano, and is particularly addressed to graduate students with a background in electromagnetism. The book is mostly suitable for master students in Nuclear Engineering, in Engineering Physics, and in Physics, but it is recommended also to students in material sciences or similar, and to PhD students. The text is organized with the objective to be suitable for both classroom teaching and self-study by students. Our aim is to provide a comprehensive and unified description of high-intensity short laser pulses and of their applications at the simplest level compatible with a correct physical understanding. The idea is to provide an intuitive picture of the phenomena under consideration, with simple mathematical description, when useful for a better understanding.

The first two chapters of the book are devoted to high-energy ultra-short laser pulses. We study the aspects concerning their generation and their propagation; we deal with all the modifications that occur, in this regime, to the spatial profile, the temporal shape, to the instantaneous frequency and the central wavelength, to the wave front, and with the amplification of the intensity. Chapter 3 describes the technological solutions which are adopted in laser systems delivering high intensity short pulses: solid state bulk strategies, high power fiber lasers and the approach based on the optical parametric chirped pulse amplification. The last three chapters focus on a few important applications: chapter 4 discusses the high-order harmonic generation and the production of XUV attosecond pulses; chapter 5 shows the principles of laser-driven acceleration of electron, protons and ions; chapter 6 deals with the principles of laser-driven inertial confinement fusion. The appendixes consider some specific topics in more mathematical detail, such as an ab initio derivation on linear and nonlinear light matter interaction, and a treatment on the conditions for the achievement of transform limited pulses.

Milano, 20 February 2020

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Laser Pulse Transformations

Laser is the acronym of light amplification by stimulated emission of radiation, a the process due to interaction of light with matter. This word nowadays identifies devices which produce electromagnetic (em) waves by stimulated emission and have particular and peculiar characteristics (usually referred as coherence, directionality, brilliance, monochromaticity/short time duration). These waves and their propagation through media or optical systems can be described by the Maxwell's equations.

In the following, we assume that the laser beam has already been generated by a suited laser cavity (an exhaustive and comprehensive description of this can be found in Ref. [1]). This beam is characterized by spatial profile (mode), temporal shape, frequency and amplitude. In this chapter we describe the laser beam and the transformations that it undergoes during propagation through media. Here we deal with *passive* modifications, that are a set of changes due to interactions with matter, either unavoidable either setup by purpose. In the next chapter, instead, we will tackle the *active* control of some characteristics of the laser beam, i.e. the real time control and manipulation of the beam, with possible feedback loops. The passive transformations that we study here are modification of the spatial profile, frequency conversion and changes of the temporal and spectral shape in case of laser pulses. The amplitude variations, and in particular amplifications, will be described in the last section of this chapter.

We emphasize that all of the mentioned transformations are the key towards high intensity, high peak power laser pulses. As a matter of fact, it is possible to achieve high amplitude, short time duration and small spot size, only with a fine control and precise manipulation of the aforementioned laser beam parameters. Moreover, fine adjustment of these quantities allows to tailor laser pulses on specific requirements for any possible applications. Note that a laser pulse is a quite complex physical element; the capability to grasp and deal with all its aspects is important for its use in practical applications.

In this first chapter, we start with a brief introduction on fundamental quantities that describe a laser pulse. We then (i) go through transformations in the space domain, with attention to self-focusing and beam quality parameters, (ii) we discuss modification in the temporal and, consequently, spectral domains, due to nonlinear effects, (iii) we study the possibility to change the central frequency (*frequency conversion*), for monochromatic and broadband waves and (iv) we finally address the change of the intensity (*amplification*) through optical parametric amplification and stimulated emission.

1.1 Electromagnetic waves: continuous wave and pulsed regimes

In an unlimited, homogeneous, isotropic medium, with no localized/free charges and currents, from Maxwell's equations we can obtain the *source-free vector wave equation* for the electric field $\mathbf{E}$

$$\nabla^2\mathbf{E} - \frac{1}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2} = 0 \tag{1.1}$$

and similarly for the field of magnetic induction $\mathbf{B}$, with $c^2 = \frac{1}{\varepsilon\mu} = \frac{n}{c_0}$, $n = \sqrt{\varepsilon_r\mu_r}$ the *index of refraction* of the medium, ε the permittivity of the medium ($\varepsilon_0\varepsilon_r$), μ the permeability of the medium ($\mu_0\mu_r$) and c_0 the speed of light in vacuum. A solution is given by a plane harmonic monochromatic wave:

$$\mathbf{E}(\mathbf{r},t) = \frac{1}{2}\left(\mathbf{E}_0 e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})} + c.c.\right) \tag{1.2}$$

which can be reduced to a scalar form, if there is a dominant component, along its local polarization direction:

$$E(\mathbf{r},t) = \frac{1}{2}\left(\tilde{E}_0 e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})} + c.c.\right) \tag{1.3}$$

with $\tilde{E}_0$ the complex amplitude, ω the *angular frequency* (usually referred simply as *frequency*), $\mathbf{k}$ is the *wave vector* and k the *wavenumber* such that $k = \dfrac{\omega}{c} = \dfrac{2\pi}{\lambda}$, λ the wavelength, and $c.c.$ stands for the complex conjugated.[1] The electric field can be also written as:

$$E(\mathbf{r},t) = \frac{1}{2}\left(\hat{E}_0 e^{i(\phi(\mathbf{r},t))} + c.c.\right)$$

with $\hat{E}_0$ real, when it is convenient to highlight the *phase* term ϕ of the wave.

For slow transverse variations the field can be approximated by *transverse electric and magnetic* (TEM) waves. In TEM waves both the dominant electric and magnetic field polarizations lie approximately in the plane perpendicular to the propagation direction. We may also assume that the polarization direction does not change substantially within a propagation distance comparable to the wavelength, and in general we deal with uniform polarizations (e.g. linear or circular).

We can define the instantaneous intensity as the energy that flows in the unit time through the unitary surface placed orthogonal to the propagation direction

[1] Analogous form is given by taking the real part: $\mathbf{E}(\mathbf{r},t) = Re\left(\mathbf{E}_0 e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}\right)$ and sometimes $\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}$ is used for conciseness; in all cases it is important to remember that whatever mathematical notation is used, the physical quantities are given by their real parts. Note also that the phase term $i(\omega t - \mathbf{k}\cdot\mathbf{r})$ can be replaced by $i(\mathbf{k}\cdot\mathbf{r} - \omega t)$ without physical differences.

of the wave and the *intensity mean value* as the mean value of the instantaneous intensity over a period, which results to be given by:

$$I(\mathbf{r}) = I = \frac{\mid E_0 \mid^2}{2Z} \tag{1.4}$$

which is usually called simply *intensity*, with $Z = \sqrt{\frac{\mu}{\epsilon}}$ the *impedance* of the medium. Actually, this is the quantity detected by instruments (that cannot follow the fast oscillations of the field, as the period is of the order of a few femtoseconds for laser emission at around $1\mu m$ wavelength).

The plane wave of Eq. 1.2 corresponds to the continuous wave (cw) regime, with constant intensity in time. Despite quite unrealistic, the monochromatic plane wave can be used as a useful approximation in certain cases.

Let us now consider another solution of the Maxwell equations[2] , consisting on the *superposition* of monochromatic plane wave components, at frequencies ω, variable around a *central frequency* ω_0, with complex amplitudes which vary with ω, $A(\omega)$. For the sake of simplicity, consider plane waves with the same dominant components (that is polarized along the same direction, x), traveling in z direction. In this case, the total electric field is:

$$E_x(z,t) = \frac{1}{2} \int \left[A(\omega) e^{i\left(\omega t - k(\omega) z\right)}\right] \mathrm{d}\omega \quad + c.c. \tag{1.5}$$

Eq. 1.5 corresponds to an infinitely dense sum of monochromatic waves over the whole frequency range $(-\infty, +\infty)$. The wave number k in general is a function of ω, the relation depending on the material and it is described by the *dispersion relation* $k = k(\omega) = \frac{\omega}{c_0} n(\omega)$. n is a complex number, where the real part describes the dispersive properties (dispersion), while the imaginary part accounts for absorption. We now consider the common case of a wave with frequencies far from the resonances of the atoms of the medium (so that we can neglect absorption, and n is real). We further consider $A(\omega)$ to be non-zero in a small (very small) region around ω_0 (with a width $\Delta\omega$). It can be shown that the em wave is a *wave packet* or a *pulse* and can be written as the product of a bell-shaped envelope function F, propagating at a velocity v_g, and a *carrier* at frequency ω_0, travelling with velocity v_f:

$$E_x(z,t) = F(z - v_g t) \quad \cos\left(\omega_0 (t - \frac{z}{v_f})\right)$$

with v_f the *phase velocity*, and v_g the *group velocity* defined as: $v_f = \frac{\omega_0}{k_0} = \frac{c_0}{n}$ and $v_g = \left(\frac{\partial \omega}{\partial k}\right)_{\omega_0}$.

If we fix z, taking for instance $z = 0$, equation 1.5 is:

$$E_x(t) = \frac{1}{2} \int \left[A(\omega) e^{i(\omega t)}\right] \mathrm{d}\omega + c.c.$$

so $E_x(t)$ and $A(\omega)$ are linked by the Fourier transform.

[2]more details can be found in Appendix A.