

# 1 Introduction

If you are looking at this book at a typical reading distance of about 50 cm, the light already requires 1.7 ns to travel the distance from the paper surface to your pupil. Since a single signal transmission between two neurons takes about 50  $\mu$ s, the image acquisition and its forwarding to the brain requires several milliseconds.

The pulses of femtosecond lasers, however, the shortest events created by mankind so far, are still shorter by several orders of magnitude compared to these timescales.

A state-of-the-art amplified femtosecond laser which typically emits pulses with a length of 100 fs and a pulse energy of 1 mJ at a frequency of 1 kHz generates flashes of light possessing a spatial length of only 30  $\mu$ m, for example. This is approximately half the diameter of a human hair. Even in nature only elementary reactions, such as atomic oscillation, the formation or disintegration of molecular bonds or the charge transfer in semi-conductors, take place within comparable periods of time.

Since time segments in the dimensions of femto- or picoseconds<sup>1</sup> are normally beyond our imagination, they can only be illustrated by way of comparison (fig. 1).

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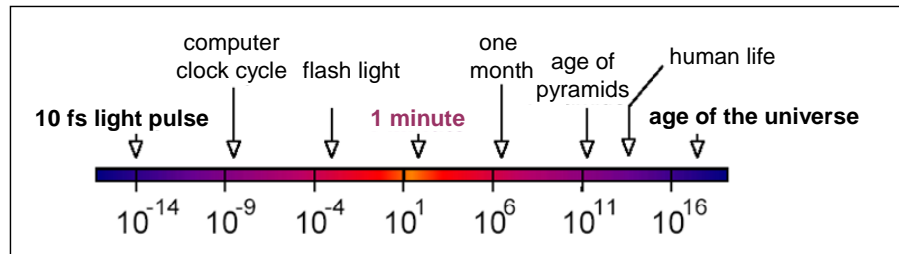
<sup>1</sup> 1 fs =  $10^{-15}$  s, 1 ps =  $10^{-12}$  s

**illustration of ultrashort pulse lengths**

The ratio of one femtosecond to one second is the same as that of one second to a period of 32 million years or that of five minutes to the total age of the earth.

The comparison that the proportion between 10 fs and one second equals that between one Euro Cent and the complete national debt of the German Federal Republic may also give an impression of the regarded dimensions.

fig. 1:  
*temporal dimension of ultrashort laser pulses*



$$\frac{1 \text{ fs}}{1 \text{ s}} = \frac{1 \text{ s}}{32\text{M years}} = \frac{5 \text{ min}}{\text{age of the earth}}$$

$$\frac{10 \text{ fs}}{1 \text{ s}} = \frac{1 \text{ Euro Cent}}{\text{national debt of Germany}}$$

The technology of ultrashort pulse lasers (USP lasers) provides the potential to control photons in the range of femto- and picoseconds and to use them in these temporal dimensions as a tool for influencing matter.

It is the aim of this book to demonstrate and to explain the fundamentals, the challenges and the potential of this technology. At first, the special characteristics of the interaction between ultrashort laser pulses and matter are described and an overview on physical and technological principles of their generation is given. A subsequent market and technology survey deals with

**aim and composition of the book**

the current status of USP beam source development and presents individual application areas, where USP lasers are already applied in practice, as they offer particularly favourable solutions, due to their special characteristics.

## 2 Interaction of Ultrashort Pulses with Matter

A detailed consideration of the interaction phenomena of laser pulses with matter is essential in order to distinguish the exact limit between short and ultrashort pulses.

A material which is exposed to a conventional laser beam absorbs the energy contained in the photons in a surface layer and transforms it into heat. If the energy density of the laser radiation is adequately high, the temperatures that are thus generated cause a local melting or evaporation of the material.

The shorter the laser pulses get and the more energy they possess, however, the more precisely the single steps of this process have to be distinguished from each other. Effects such as the interaction of the laser pulses with the ablation plasma or shockwaves that are caused by plasma expansion can influence the process. With short pulse lengths, whose time expansion is in the range of the duration of thermal conduction and diffusion processes within the material, the thermal interaction mechanisms are increasingly losing relevance. The process is getting dominated by special photo-chemical effects that can only be observed when ultrashort laser pulses interact with matter. As a precise example, the interaction of an ultrashort laser

**interaction of  
conventional  
laser radiation  
with matter**

pulse with a metallic surface takes place in the following order and timescale:

The photons, hitting the material, are absorbed within a few femtoseconds by free electrons in a certain absorption volume reaching from the material surface to the optical penetration depth. The thickness  $\delta$  of the absorption layer, where the predominant part of the laser energy is absorbed, is calculated by means of the material- and wavelength-dependent absorption coefficient  $\alpha$  according to

$$\delta = 2 / \alpha .$$

For metals, the thickness  $\delta$  at a laser wavelength of about 800 nm lies in the range of 10 nm. The relaxation time of the electrons amounts to approx. 1 ps. Thus, the energy of the laser pulse is stored in the electrons for 1 ps and then transformed into heat and passed on to the lattice. This heat diffuses from the surface layer to the interior of the material. The thermal diffusion depth  $d$  is a function of the time  $t$  and the diffusion coefficient  $a$

$$d = \sqrt{4at}$$

and also amounts to approx. 10 nm after 1 ps in the regarded case. If a metallic sample is hit by a laser pulse with the length of 1 ps, the optical penetration depth of the photons thus corresponds to the thermal diffusion depth during the length of one pulse. The definition of an ultrashort laser-matter interaction for

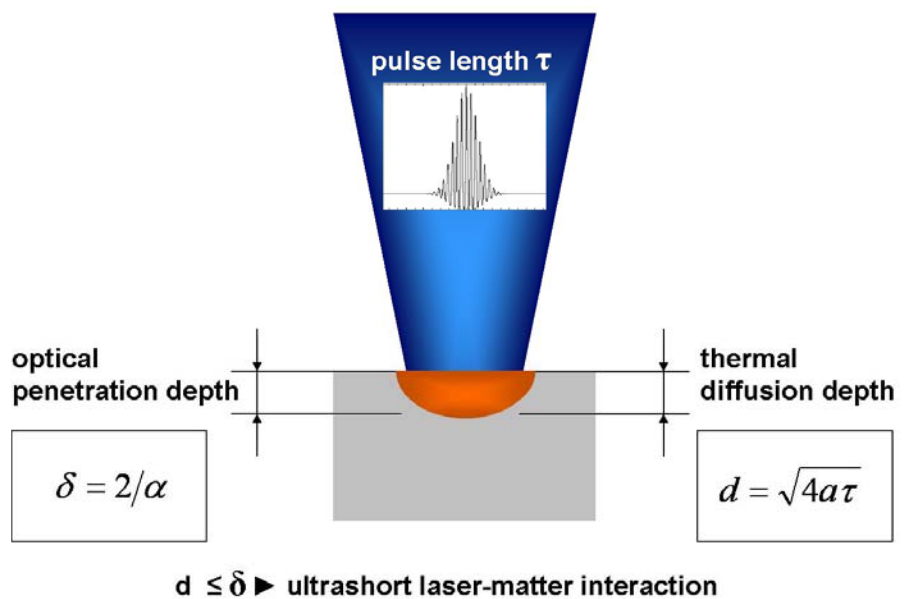
material aspects can be derived from this examination [1]:

**definition**

**“ultrashort” laser-matter interaction**

A laser pulse is to be classified as ultrashort, if the thermal diffusion depth, which is reached during the length of the pulse, is of the same dimension or smaller than the optical penetration depth of the laser light into the examined material (cf. fig. 2).

fig. 2:  
*ultrashort laser-matter interaction*



**differentiation**

**short / ultrashort pulses**

Since material-dependent coefficients were used in the formulas above, this definition which sets the limit between short and ultrashort pulses for metals at approx. 1 ps and for ceramics at approx. 10 ps is material-specific. For certain polymers with low heat conductivity, pulses with a length of 1 ns can already be classified as ultrashort according to this definition.