2. Absorption of Laser Light

Laser light, in order to cause any lasting effect on a material, must first be absorbed. As trivial as this may sound, absorption very often turns out to be the most critical and cumbersome step in laser processing. An enormous amount of work has been dedicated to investigating laser absorption mechanisms under various circumstances, and a great deal can be learned from this work for the benefit of laser materials processing.

The absorption process can be thought of as a secondary "source" of energy inside the material. Whilst driven by the incident beam, it tends to develop its own dynamics and can behave in ways deviating from the laws of ordinary optics. It is this "secondary" source, rather than the beam emitted by the laser device, which determines what happens to the irradiated material.

Section 2.1 is meant as a refresher and as a basis for subsequent discussions. It summarizes the familiar optical properties of condensed matter, as far as they are relevant to absorption. The following two sections then treat modes of optical behavior influenced by intense laser irradiation, arising from atomistic and from macroscopic material responses, respectively.

2.1 Fundamental Optical Properties

2.1.1 Plane-Wave Propagation

The simplest form of light is a monochromatic, linearly polarized plane wave. This will, for most of our purposes, be a sufficient approximation of a real laser beam. The electric field of a wave propagating in a homogeneous and nonabsorbing medium can be represented as

\[ E = E_0 e^{i(2\pi z/\lambda - \omega t)} \]  

(2.1)

where \( z \) is the coordinate along the direction of propagation, \( \omega \) is the angular frequency, and \( \lambda \) is the wavelength. The last two quantities are related

\[ \lambda = \frac{c}{\omega} \]

\[ \omega = \frac{2\pi}{\lambda} \]

\[ c = \frac{2\pi}{T} \]

where \( c \) is the speed of light, and \( T \) is the period of the wave.

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\[ ^1 \text{Here and in what follows, we shall interpret the words "optical" and "light" generously such as to cover the whole range of wavelengths (between roughly 0.1 and 10 \( \mu \)m) currently of interest in laser materials processing.} \]

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through the phase velocity $c/n_1$, $c$ being the speed of light, and $n_1$ the refractive index of the medium [$n_1 = 1$ in vacuum; it is hardly different in air at standard temperature and pressure (stp)] by

$$\lambda = \frac{2\pi}{\omega} \frac{c}{n_1}.$$ (2.2)

An expression analogous to (2.1) also holds for the magnetic field $\mathbf{H}$. The magnetic and electric field amplitudes are related by

$$\mathbf{H}_0 = n_1 \varepsilon_0 c \mathbf{E}_0,$$ (2.3)

with $\varepsilon_0$ being the dielectric constant in vacuum. On average, the electric and magnetic fields each carry the same amount of energy. However, in the force $f$ exerted by the electromagnetic wave on an electron

$$f = -e \left[ \mathbf{E} + (n_1/c)(\mathbf{v} \times \mathbf{H}) \right]$$ (2.4)

the contribution due to the magnetic field is smaller than that due to the electric field by a factor of the order of $v/c$ ($v$ being the electron velocity), and hence it is usually negligible. It is the term $-e\mathbf{E}$ in (2.4) that ultimately produces just about every phenomenon discussed in this book.

The energy flux per unit area of the wave is termed irradiance\(^2\) and given by

$$I = |\mathbf{E} \times \mathbf{H}| = n_1 \varepsilon_0 c \mathbf{E}_0^2.$$ (2.5)

In the language of quantum mechanics, a wave of angular frequency $\omega$ and irradiance $I$ corresponds to the flux $I/\hbar \omega$ of photons of energy $\hbar \omega$. Light interacts with matter only in portions of whole quanta. However, while quantum mechanics is required to understand the microscopic aspects of this process, the photon fluxes in intense laser beams are enormous and classical concepts are generally adequate to describe beam-solid interaction phenomena.

The concept of a beam implies that the irradiance is maximum near the optical axis and falls off laterally. The most common lateral distribution is a cylindrically symmetric Gaussian

$$I(r) = I_0 e^{-r^2/\omega^2}.$$ (2.6)

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\(^2\) The term "intensity", often used instead, denotes the energy flux per unit solid angle.