Fundamental Knowledge

Part 1

Ever since scientists started investigating our world, two aims have had the highest priority. One simply understands how everything around us is organised. The other is using this knowledge to make our lives more productive and comfortable. Much of our mental potential is developed by applying our 5 senses in direct day-to-day practice. Of the 5 senses, sight is a critical tool with very high potential and bandwidth for extracting information making it a powerful interface for gathering knowledge.

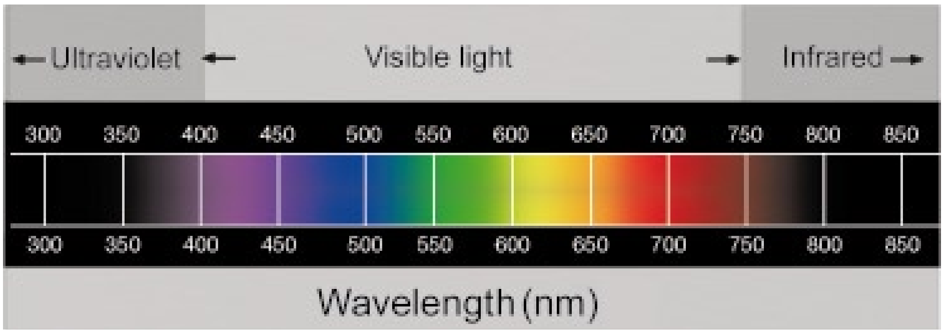


Fig. 1: Schematic display of the visible spectrum of electromagnetic radiation and the resulting colour ranges.

"I saw it with my own eyes!" – think about the significance of that expression. It provides a hint as to why optical microscopy is such a popular method for exploring the structures of materials. All other information received by instrumental sensory technologies in materials science research enters our minds via some secondary visualisation process. Though optical microscopy itself makes increasing use of integrated digital technology for interfacing image information, it is still closest to the actual process of seeing with the naked eye – i.e., receiving image information directly.

How do people actually receive information about their surroundings? How does a person receive the image information offered via a microscope? The information-bearing medium is visible light and the information it carries is as a result of its various interactions with physical matter. The electromagnetic radiation of visible light is the point of departure for light microscopy in general, as well as in the metallography field. It is necessary to understand terms such as reflection, polarization and interference, alongside fundamental quantities closely linked to them such as amplitude, radiation and phase shift. This facilitates grasping the various light-microscopical contrast and imaging procedures for metallography, which involves a good deal of fundamental knowledge on the physical nature of light. This part of the chapter is from one of our "Digital Materials Analysis" series, and therefore, deals with the optical fundamentals of light and the interaction with a sample. Subsequently, the light microscopy that is commonly used in metallography is introduced and explained in part two. The final segment deals with the contrasts that play an important role in imaging metallographic samples.

Optical Fundamentals

The fundamentals described below on light properties focus on the information needed to understand the material presented and are not exhaustive. For more advanced detail and more sophisticated theoretical fundamentals, we would advise interested readers to consult the extensive web pages of Florida State University, for example, on microscopy and the related physical background information (www.microscopy.fsu.edu/primer/index.html).

Visible Light

In everyday language, light is understood as the range of electromagnetic radiation that we can see with the naked eye. This comprises a wavelength spectrum of ca. 400 nm–750 nm. The colours of light that can be seen by the eye occur due to varying wavelengths and their blending (fig. 1). The adjoining spectra from the deep-red and infrared range (to 1200 nm) as well as the near ultraviolet light (200–380 nm) are used in light microscopy. Even though these segments of the spectrum are not visible to our eyes, these segments can be acquired using suitable detectors, CCD cameras for example, and made available via a monitor for imaging or analysis.

Wavelength, Frequency, Energy

The smallest distance between two points of the same phase of a wave is referred to as wavelength λ (fig. 2). The two points are precisely in the same phase when they have the same deflection, ie, amplitude (A), and move in the same direction through time. The wavelength of light has a direct correspondence with the frequency, as does any other form of electromagnetic radiation (ν): i.e. it is inversely proportional. When entering or traversing a medium, the speed and wavelength of the light are changed. The frequency, however, remains unchanged.

Alongside its wave properties, light is quantified in photons. A photon (quantum of electromagnetic energy) is considered the smallest amount of energy of any frequency of electromagnetic radiation. The energy of a photon is directly proportional to frequency and thus indirectly proportional to wavelength. This means that energy increases as frequency increases and wavelength shortens. This is why shortwave radiation is dangerous, since it has high energy in a narrow range. It can have dangerous effects on organisms, for example there is a well known correlation between UV light and skin cancer.

The brightness of light perceived by an animal depends on the number of photons that reach the eye per unit time. It can be described, albeit simply, as the amount of wave deflection or amplitude (fig. 2). Other factors are the colour or wavelength and contrast (to the background) as well as its expansion. The eye's sensitivity to brightness is greatest with green-yellow colour tones (500–560 nm). In this case, small points of light are interpreted as brighter than larger ones of other colours, even though they have the same physical light intensity. The eye can discern 50–60 levels of

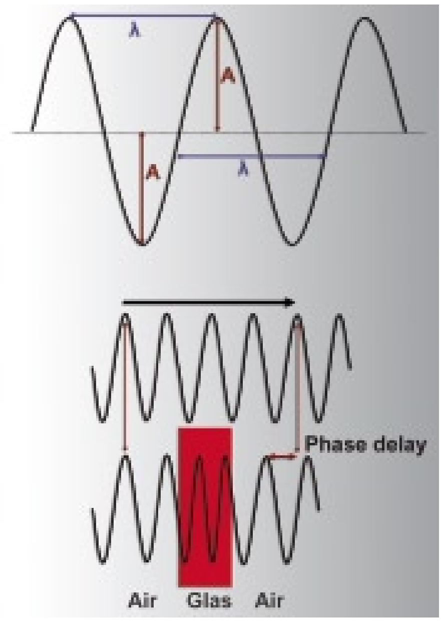


Fig. 2: Schematic diagram of waves with the wavelength (λ), of the smallest distance of two points of the same phase of a wave and of the deflection height (amplitude: A). The lower example shows how a wave of light is phase delayed when passing through an optically denser medium (eg, glass or a cell). The amplitude remains practically the same.

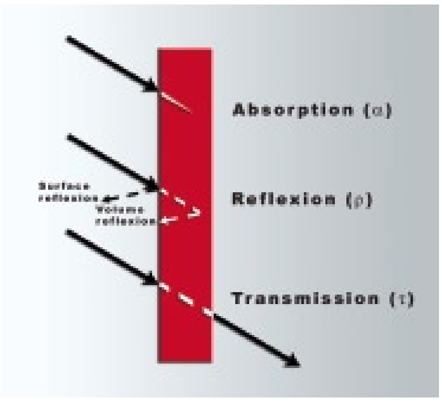


Fig. 3: Reflection is where electromagnetic radiation is deflected and "bounced back". This takes place either at the boundary between two media (surface reflection) or within the interior of a medium (volume reflection). Transmission is the expansion of electromagnetic radiation passing through a medium. Diffusion can take place in both phenomena. Diffusion is where a ray of light with a certain dispersive direction is deflected in many different directions (diffuse reflection or diffuse transmission). If there is no scattering upon reflection or transmission, the ray of light is deflected in a certain direction in accordance with the physical laws of optics (directed light reflection or transmission). Reflection, transmission and scattering do not alter the frequency of a wave. Absorption is the conversion of radiation into a different form of energy (usually heat) that occurs upon the interaction of radiation with matter.

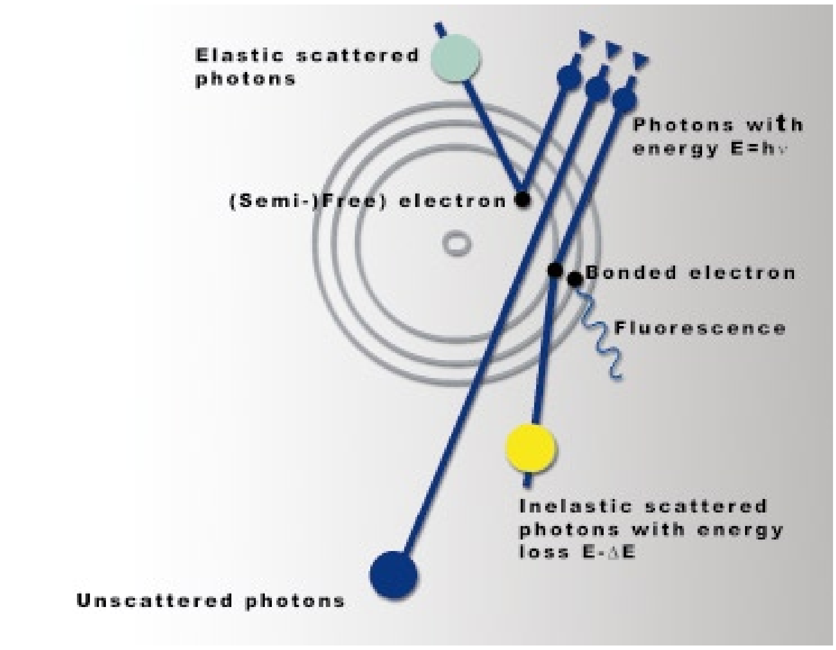


Fig. 4: When photons encounter a surface there are various interactions with the electrons and the material. Fluorescence may occur, which is the absorption of light of a particular wavelength (excitation light) involving various molecules and the simultaneous emission of light at longer wavelengths.

brightness in gray-scale images. A computer monitor on the other hand shows images with 256 gray scales (8 bits) and digital cameras, depending on the model, can acquire up to 4096 gray scales (12 bits) – inasmuch these are actually present in the image. These numbers show how digital image acquisition exponentially expands what image analysis can do – especially compared with viewing a sample with the naked eye alone.

Light – Object Interactions

As soon as light encounters an object, three phenomena can take place: reflection (ρ), absorption (α) and transmission (τ). These processes, and their respective interrelationships, vary depending on the object's parameters – such as material (refraction index n), surface, thickness (absorption coefficient μ) and colour. Important effects such as polarization or interference are direct results of these phenomena, which are decisive for contrast formation, imaging and material detection in the incident light microscope used for metal microscopy.

Absorption and Scatter

In our day-to-day lives we experience how colourless light, also frequently referred to as white light, can diminish in brightness due to absorption. This explains how much brighter a room looks after the windows have been cleaned. When a wave is absorbed by an absorbent, homogeneous material, the absorption probability (per unit of length) is the same at any penetration depth. According to the Beer-Lambert law, the amount of photons non-absorbed or scattered in the process depends on the layer-thickness of the material. This explains why the sky seems darker and the sun appears brighter in the mountains.

But it's not just the intensity that decreases. The light absorption of surfaces is usually dependent upon frequency and also varies in strength according to the surface colour. This kind of frequency-dependent absorption alters the remaining wavelength characteristic of the light, which results in us seeing colours.

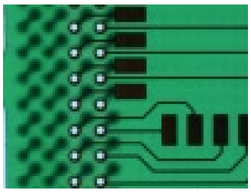
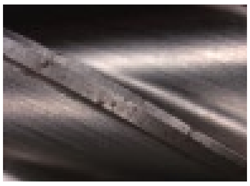
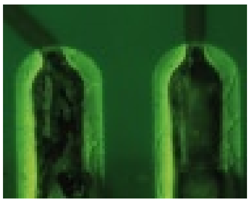
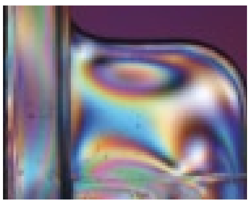
Absorption is caused by scatter, i.e. the interactions of the light quanta with the free and bonded electrons of the material. Elastic and inelastic scattering are of decisive significance here. Elastic scattering is where the sum of energy of the incident photons is too small to excite the atom. The energy of the scattered photon remains unchanged but its direction changes (fig. 4). Inelastic scattering is where the photon loses a part of its energy as excitation energy of an atom or during ionization processes (fig. 4). After scatter, the scattered radiation usually has an altered diffusional direction. Inelastic scattering also means changed energy (frequency ν) and sometimes altered polarization direction.

Table 1 describes how materials science visual effects are linked to both elastic and inelastic scattering.

Refraction and Refraction Index

Various transparent media such as air, water and glass slow down the light passing through them (phase shift) to differ-

Table 1: Overview of interaction of photons and matter

Visual effect	Typical materials	Physical origin	Images
Total transparency accompanied by gradual reflection	Most gasses, some liquids, some mineral substances like glass (SiO_2), quartz and other crystalline structures of similar physical behaviour with smooth surfaces and homogeneous structure. Depending on their refractive index they are used for optical imaging lenses.	Elastic scattering of photons in interaction with electrons, which are bound by electromagnetic forces in an atomic /molecular system. The system structure must either be completely homogeneous or of high crystalline order. Smooth interfaces to other matter or vacuum, like polished glass to air, cause almost no irregular effect on interference. Interfaces between media with different refraction indexes result in correspondingly clear reflectivity.	
Diffuse transparency	As above, but contaminated with scattering substances or diffused interfaces.	Colourless, transparent matter with statistically irregular interfaces of different refractive indices (changes the speed of light) cause elastic scattering in all spatial directions due to interference effects	
Total reflectance	All metals and other materials whose physical behaviour does not bind electrons by strong individual forces to an atom or molecule. Electrons behave like a free moving gas only weakly bound to the entire material structure. (Depending on their reflectance behaviour these materials are used for producing mirror devices for optical instruments.)	Elastic scattering of photons in interaction with electrons which form a common electrical field. The electrons are just weakly bound to an atomic or molecular structure; this explains their absorbent behaviour towards the photon, though the photon is immediately remitted (repelled). Surfaces need to be perfectly smooth.	
Remittance	Non-polished, clean, metal surface without oxidation contamination.	Same as in clear reflectance but with a surface design which causes diffuse reflection due to interference effects.	
Absorption	Most organic and inorganic materials show strong absorption and are termed opaque. To obtain information about their interaction with photons, these materials can be prepared as thin locally homogeneous layers so they still transmit relevant numbers of photons to describe the absorption behaviour.	Various effects of inelastic scattering of photons in interaction with electrons, whereby the absorbed photon energy typically dissipates inside matter as thermodynamic energy. Absorption is typically energy dependent, whereas it is often that just bands of photon energy are absorbed by individual matter. Specific inelastic scattering effects may leave photons with reduced energy (Raman scattering).	
Fluorescence/ Luminescence	Complex organic molecules and semiconducting crystalline structures (quantum dots) are typically used for showing fluorescence.	Inelastic scattering of photons which leads to energy exited status of electrons in matter. Depending on the type of molecule the absorbed photon energy is released after some characteristic time period in form of lower energy photons which are remitted or absorbed in secondary processes. Portions of absorbed photon energy may dissipate to the matter as thermodynamic energy.	
Polarization	Clean, smooth, metal surfaces show a dependency on photon interaction (dependent on their polarization). The parameter is the angle of the photon incidence towards the surface. Most natural crystalline minerals show anisotropy in absorbing or transmitting to the photon polarization as well. (birefringent materials such as quartz or calcite are familiar examples).	The most tricky, as the photon force acts dynamically, changing symmetrically along an axis perpendicular to the propagation direction and kept in this state as long as the photon exists. Any anisotropy of matter in terms of polarity in interacting with electromagnetic forces will determine whether one of the interactions named above with a polarized photon will take place at all.	

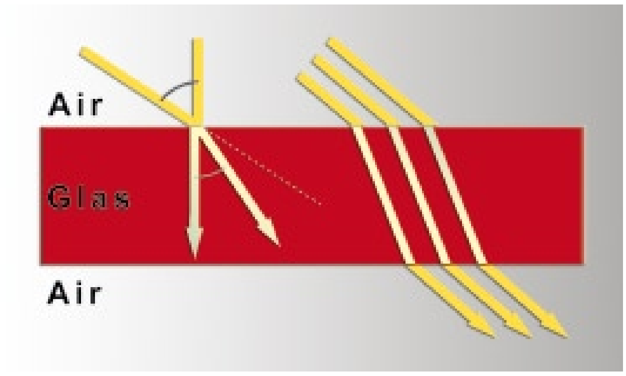


Fig. 5: Diagram of the refraction of light. Light that enters into an optically denser medium at an angle is refracted toward the perpendicular. When it exits, it is subject to the reverse deflection and is thus parallel shifted.

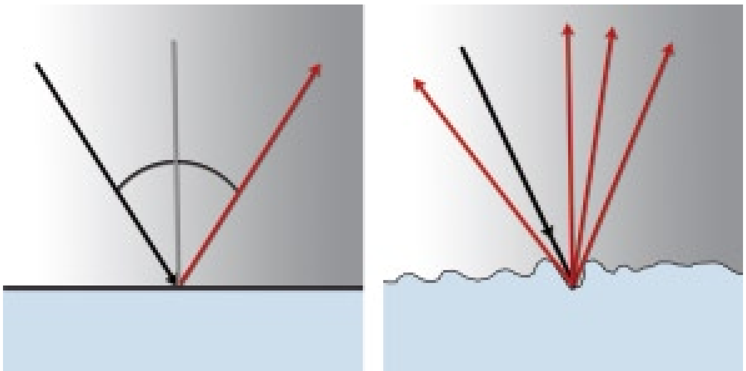


Fig. 6: The law of reflection applies to smooth surfaces. This states that the incident ray, the perpendicular of incidence and the reflected ray are all within one incident plane and the incident angle is always exactly the same as the reflection angle. Boundaries with a greater roughness relative to the wavelength, on the other hand, reflect diffusely.

ing extents, dependent on their optical density. When light from a medium (e.g., air) enters into another medium with a higher optical density (e.g., glass) at an angle, the light is not only slowed down, but also refracted. This means that the light is deflected in an angle specific to the two media. When the light exits and encounters a medium with a lower density (e.g., air) the speed is once again specific to this medium and it is subject to a reverse deflection. The ray of light in this example is thus parallel shifted (fig. 5).

There is a value that indicates the extent of refraction for transparent media – the refractive index n. This is 1 for air and increases with the optical density of the medium (e.g., water n = 1.33). Oils that are used in microscopy for high-resolution or powerful magnifying objectives (for immersion of the frontal lens) have a refraction index of ca. 1.51.

Reflection

If electromagnetic waves are deflected back from the material, this is termed reflection. With smooth surfaces, the light reflects according to the physical principle: entry angle equals exit angle. This means that every ray of light is reflected in precisely one direction. Boundary layers with significant roughness relative to the wavelength, reflect diffusely. If the material contains many scatter centres, the reflection follows the Beer-Lambert Law, whereby the main back scatter takes place perpendicular to the material, independent of the incident direction. Thus, if a ray of light encounters a rough surface, it is reflected in all directions spatially.

Interference

Various waves of light can interact with one another. These waves can also overlap each other. If the waves‘ frequencies and wavelengths are roughly the same, a new wave emerges. The new wave is amplified or weakened in comparison to the original waves – depending on the phase correspondence between the overlapping waves. This phenomenon is called interference. The waves are amplified when the phase shift corresponds to an entire wavelength. This effect is referred to as constructive interference. Wave traits are erased at a phase shift of half a wavelength (destructive interference). Any wave capable of interference is designated as a coherent wave. These are wavelengths with a constant phase ratio and equal frequency.

Polarization

Polarization is a property of transverse waves, and thus of the electromagnetic waves, which describe the direction of the amplitude vector. No polarization phenomenon, on the other hand, can occur with longitudinal waves, whose oscillation takes place in the direction of dispersion. A transverse wave has two directions. Firstly, the wave vector, which points in the direction of dispersion – secondly, the amplitude vector. This is always perpendicular to the wave vector in transverse waves. The third degree of freedom in three-dimensional space is rotation around the wave vector.

There are three distinct kinds of polarization. They differ in direction and magnitude of the amplitude vector (at a constant point in space):

linear polarization: The amplitude vector always points in a constant direction and the deflection changes its magnitude and its sign periodically (with constant amplitude) with the progression of the wave.

circular polarization (also referred to as rotational polarization): The amplitude vector rotates at constant angle speed around the wave vector and does not change its magnitude with the progression of the wave.

elliptical polarization: The amplitude vector rotates around the wave vector and alters its magnitude periodically. The peak of the field vector follows an ellipse in this instance.

Polarization methods facilitate the application of highly qualitative contrast methods such as Differential Interference Contrast (DIC). Polarization microscopy is of critical importance in microscopy of double refractive sample structures such as crystals.

Diffraction

Light that shines through a small aperture generates a pattern of bright rings referred to as a diffraction pattern. Patterns can range from a centrally bright segment (direct, unrefracted light or main maximum), followed by a number of rings with significantly less brightness (refracted light or secondary maxima). This occurs due to series of destructive and constructive interferences. According to the Abbé theory of resolution, image formation only takes place once, at least one secondary maximum interacts with the main maximum in the intermediary image plane. The more secondary maxima contributing to image formation, the higher the resolution.

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