Notes of Optical design and instrumentation

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Preface

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Chapter 1

Introduction to Optics

1.1 Introduction

1.1.1 Light propagation

Geometrical optics is the study of light in the limit of short wavelenegths. We treat light as propagating rays. Geometrical optics usually ignores interferences, diffraction, polarization and quantum effects.

It often includes:

- Reflection, refraction
- Optical design
- Imaging properties
- Aberrations
- Radiometry

Light is a self-propagating EM wave where electric and magnetic fields are perpendicular or transverse to direction of propagation. In a vacuum, light propagates at the speed of light c, which is

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 2.99792458 \times 10^8 \quad (m/s). \tag{1.1}$$

The **wavelength** λ is the distance between two peaks or two valleys on the wave.

A **wavefront** is a surface of constant propagtion time from the source. It begins from a point source in spherical form, and as it propagates away, a given solid arc tend to behaves a a planar wavefront.

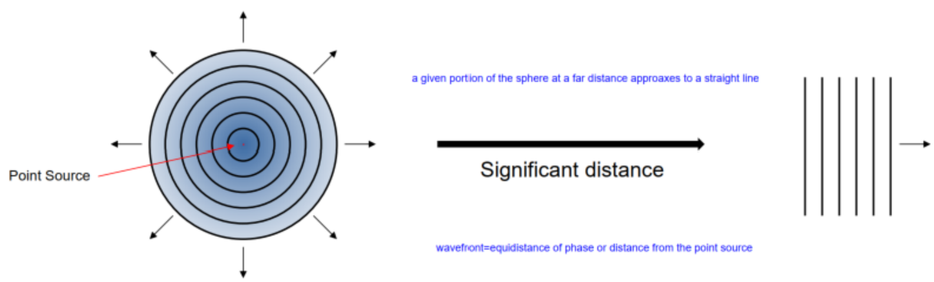


Figure 1.1 We can treat the wavefront as planar when assuming a distant object.

The time for one wavelength to pass is knwon as the **period** T:

$$T = \frac{\lambda}{V} \quad (s), \tag{1.2}$$

where V is the velocity of propagation. The number of wavelengths to pass in one second is the **frequency** ν:

$$\nu = \frac{1}{T} \quad (s^{-1})(Hz). \tag{1.3}$$

1.1.2 Sign convention

We define the sign convention for which the light propagates. It allows us to keep track of physical quantities and multiple reflections when analyzing complex optical systems.

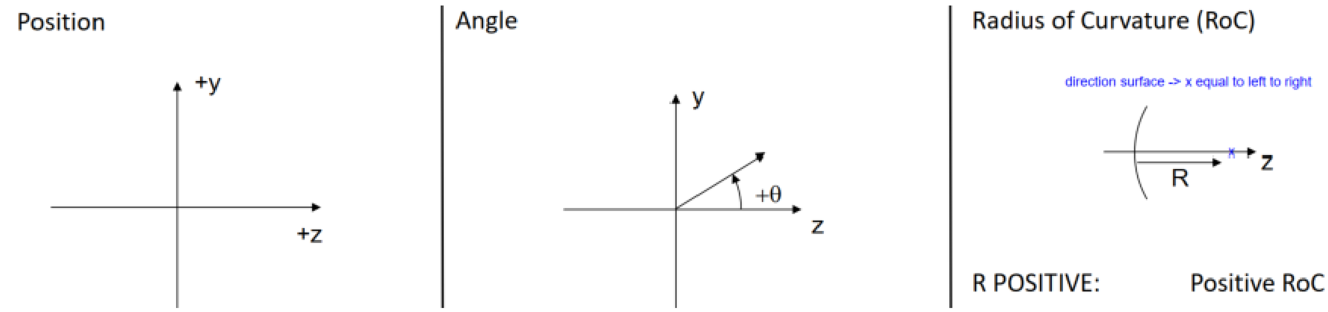


Figure 1.2

1.1.3 Electromagnetic spectrum

The light can be of various wavelengths (frequencies) which translates to the color of the light. The range of the wavelengths is called the **electromagnetic spectrum**. The **index of refraction** tells how much the

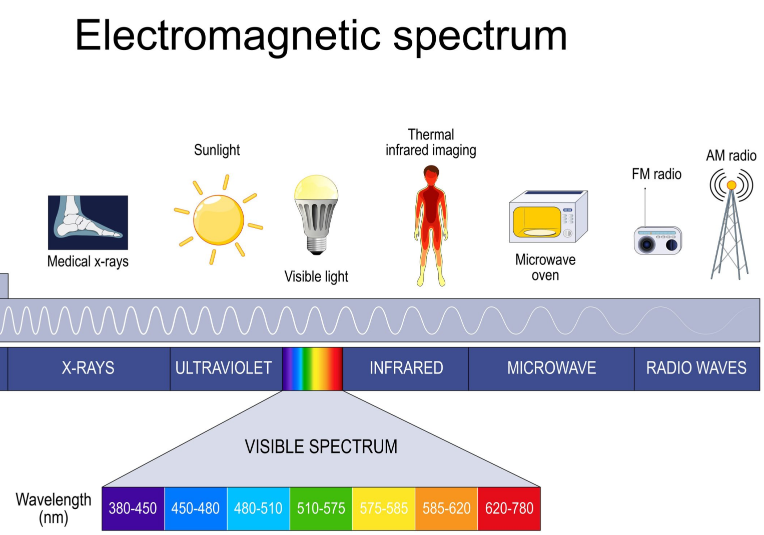


Figure 1.3

light is slown down in a medium with respecto to vacuum.

$$\text{Index of refraction} \qquad n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in medium}} = \frac{c}{V} \geq 1\,. \tag{1.4}$$

From one medium to another, the frequency remains unchanged but only the wavelength is modified. The index of refraction is a function of the wavelength and of the temperature.

> **Vaccum equal to air**
>
> In geometrical optics, vacuum and air are used interchangable as the index of refraction of air is $n \approx 1$.

1.1.4 Optical path length

The **optical path length** (OPL) is the equivalent distance in vacuum that light would cover in the same time as it takes to cross the actual medium.

$$\text{Optical path length} \qquad \boxed{\mathrm{OPL} = \int_a^b \boldsymbol{n}(s) \cdot d\boldsymbol{s}} \,. \tag{1.5}$$

When the medium is homogeneous, the index n reduces to a constant value. Consequently, the ray travels in **straight lines**.

Fermat's principle states that the path taken by the light from one point to another is the path for which the OPL is stationary:

$$\text{Fermat's principle} \qquad \boxed{\frac{d\mathrm{OPL}}{d\mathrm{path}} = 0} \,. \tag{1.6}$$

1.1.5 Snell's laws of reflection and refraction

Snell's law can be obtained from Fermat's postulate. They governs the dynamics of the ray when passing thourgh an interface of different index of refractions:

$$\text{Snell's laws} \qquad \boxed{\begin{aligned} n_1 \sin\theta_1 &= n_2 \sin\theta_2 \\ \theta_1 &= -\theta_2 \end{aligned}} \tag{1.7}$$

The angles are measured relative to the surface normal.

(a) Refraction

(b) Reflection

Figure 1.4 In refraction and reflection, the angles are taken respective to the surface normal.

> The reflection is equal to refraction with a negative index: $n = -n$.

1.1.6 Total internal reflection (TIR)

Total internal reflection occurs when the light propagating from a medium n_1 to another n_2, with $n1 > n_2$, exceed a critical incident angle

$$\text{Total internal reflection} \qquad \boxed{\theta_i > \theta_c = \sin^{-1}\frac{n_2}{n_1}} \,. \tag{1.8}$$

Under this condition, 100% of the light is reflected into n_1, and no refracted light is present.

1.2 Mirrors and prisms

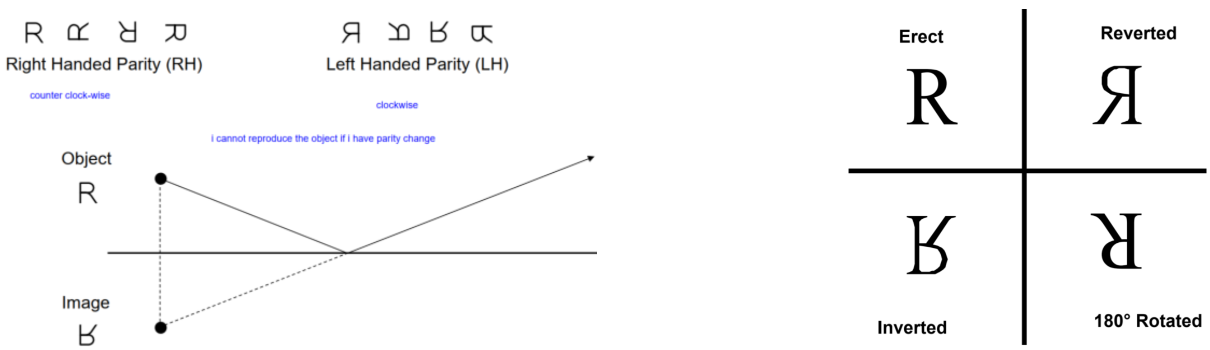
1.2.1 Parallel mirrors

Plane mirrors are used to:

- Produce a deviation
- Fold the optical path
- Change image parity

1.2.2 Parity change

A reflection from the plane mirror will cause a parity change in the image. An inversion (reversion) is a



(a) (b)

parity change about the horizontal (vertical) line, whereas a $180°$ rotation has no parity change and is rotated about the optical axis. An inversion and a reversion is equivalent to a $180°$ rotation.

> **Parity change**
>
> Only an **odd** number of reflections changes parity.

Parity is determined by looking back agains the propagation towards the obejct. Compare looking directly the objet vs at the reflection.

> A lens adds inversion and reversion to the object, so that the image has no parity change, only rotation.

1.2.3 Non-parallel plane mirror

The **dihedral line** is the line of intersection of two non-parallel plane mirrors. The ray is deviated twice the angle between the mirrors.

$$\gamma = 2\alpha = \begin{cases} \text{Input-Output rays cross,} & \alpha < 90° \\ \text{Input-Output rays diverge,} & \alpha > 90° \\ \text{Input-Output rays anti-parallel,} & \alpha = 90° \end{cases} \tag{1.9}$$

There are several mirrors,

- **Roof mirror** Two plane mirrors with a dihedral angle of $90°$. It is used to insert two reflection in the propagation. The presence of this mirror is indicated by a "V".

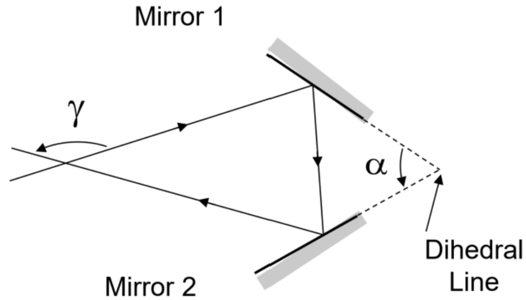


Figure 1.2

1.2.4 Prisms and tunnel diagrams

Prisms can be considered systems of plane mirrors. The reflection may be due to TIR, or by reflective coating.

A **tunnel diagram** **unfolds** the optical path at each reflection so that the ray is maintained straight through the propagation in the prism.

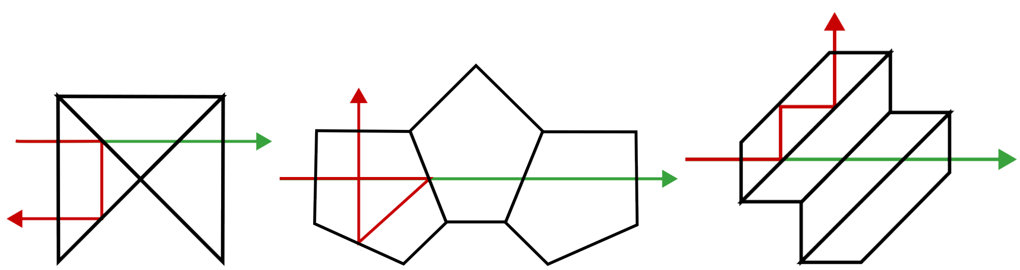


Figure 1.3

1.2.5 Reduced thickness

The **reduced thickness** is the vacuum equivalent distance of the medium that has the same propagation effect.

$$\text{Reduced thickness} \qquad \boxed{\tau = \frac{t}{n}}. \tag{1.10}$$

Expressing all distances in τ is equivalent to propagates the light in only vacuum (or air). This quantity is implicitly in the optical propagation and will be present in equations. When a reflection takes place, both n and t are negative, but τ remains positive.

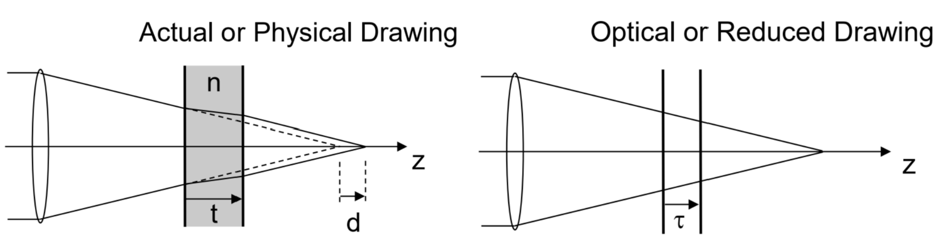


Figure 1.4 Reduced thickness is the vacuum (air) equivalent distance.

Tunnel diagrams are afected by the reduced thickness along the propagation distance. If the total distance is L, then the reduced is L/n.

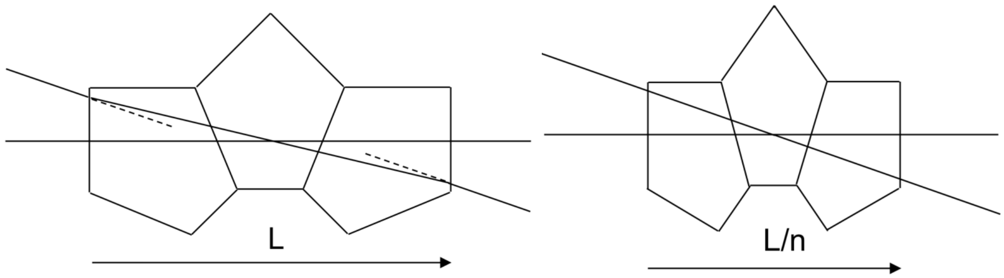


Figure 1.5 The diagram is only shortened along the direction of the propagation.

In a plate parallel plate (PPP), the beam is shifted horizontally a distance proportional to τ when is placed perpendicular ot the optical axis:

$$d = \frac{n-1}{n}t. \tag{1.11}$$

If it is disposed with an angle θ, then the ray will be shifted vertically

$$D \approx -t\theta\frac{n-1}{n}. \tag{1.12}$$

1.3 Thin lens Imaging

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