

Introduction to Optical Modeling

An optical diagram showing a series of lenses and curved surfaces on the left. Three colored lines (red, green, blue) represent light rays originating from different points and converging at a single point on the right. The red rays converge at the top, the green rays in the middle, and the blue rays at the bottom. The diagram illustrates the principles of ray optics and image formation.

Friedrich-Schiller-University Jena
Institute of Applied Physics

Lecturer:

Prof. Uwe D. Zeitner

(Part 1)

Prof. Frank Wyrowski

(Part 2)

Seminar

Bi-weekly



4 groups (about 15 students each)

Monday:

12:00 – 14:00

Start:

25.10.

Group 4

1.11.

Group 3

Friday:

10:00 – 12:00

Start:

29.10.

Group 2

5.11.

Group 1

Required:

Zemax-Account

(see next slide)

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Are

All additional information on the Moodle platform

The screenshot shows a Moodle course page for 'Optical Modeling WS 2021' at moodle.uni-jena.de. The sidebar on the left contains the following links: Badges, Kompetenzen, Bewertungen, Allgemeines, Lecture Videos, Lecture Slides, Software, Startseite, Dashboard, Kalender, Meine Dateien, and Meine Kurse. The main content area displays a 'Rechtlicher Hinweis' (Legal notice) and a 'Legal notice' section. A red circle highlights the 'Software' link in the sidebar, which points to 'Instructions for getting and installing ZEMAX' in the main content area.

Course Overview

Part 1: Geometrical optics based modeling and design (U.D. Zeitner)

1. Introduction (today)
2. Paraxial approximation / Gaussian optics
3. ABCD-matrix formalism
4. Real lenses
5. Optical materials
 - glass types, dispersion
 - chromatic aberrations
6. Imaging systems
 - apertures/stops, entrance-/exit-pupil
 - wavefront aberrations

Part 2: Wave-optics based modeling (F. Wyrowski)

Additional Literature

H. Gross, "Handbook of Optical Systems," Wiley-VCH
in particular Vol. 1 & 2

W.J. Smith, "Modern Optical Engineering," SPIE Press

J. Goodman, "Introduction to Fourier Optics," Roberts & Company Publishers

1 Introduction

Topic of the course: Optical Modeling and Design

—————→ understanding of optical systems

Examples of optical systems:

- energy → photovoltaics
- medicine → microscopes, photodynamic therapy, ...
- datacom → fiber-optical information transport, cell-phone camera, ...
- technology → fabrication of computer chips, laser material processing ...
- ...



Canon EF400



Daimler AG



Microsoft
HoloLens



Lithography

Basic Building Blocks

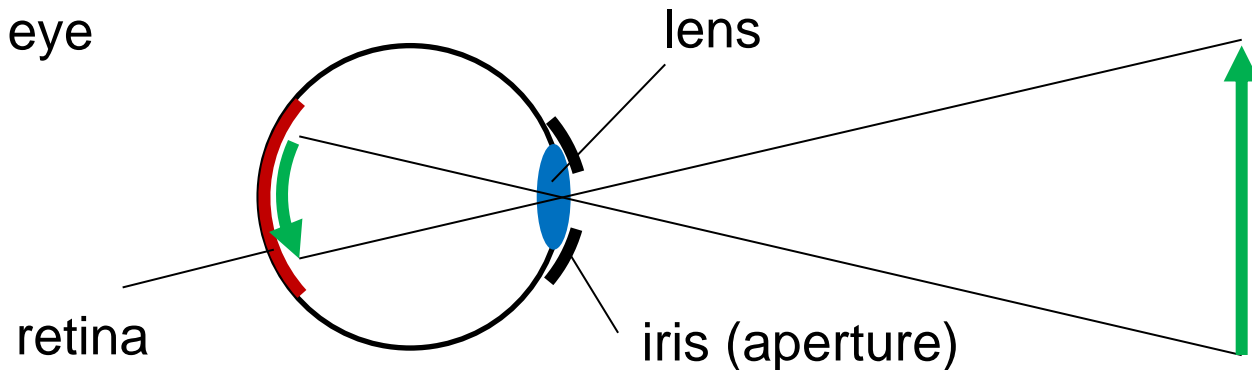
each optical system is composed of 3 basic building blocks:



- active: lamp, laser
- passive: reflected light

- eye
- CCD-camera
- film
- chlorophyll
- ...

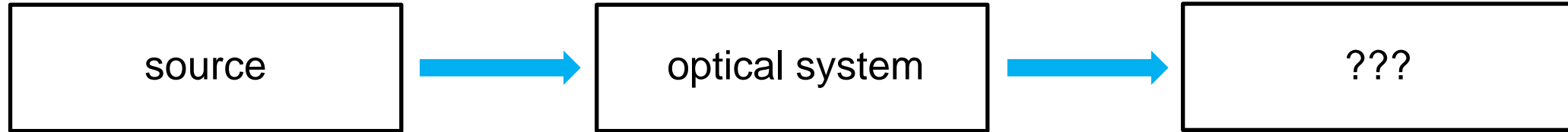
Simple example: the human eye



Modeling vs. Design

Understanding the function of a given optical system

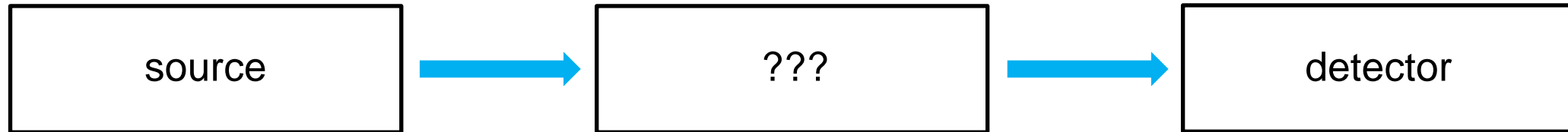
➡ **Modeling**



- requires:**
- models for proper **representation of light**
 - models for **interaction of light and matter**

Modify / optimize the function of an optical system or build a complete new one

➡ **Design**



- requires:**
- modeling of the system
 - concepts for **improvements** or ideas for good solutions
 - decision **criteria** for good solutions

} **not trivial!**
➔ **an inverse problem**

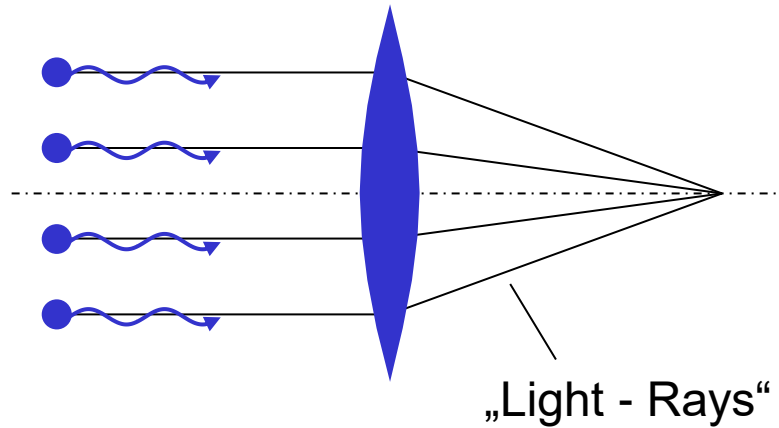
1.1 Light Representation

Fundamental Question: What is Light?

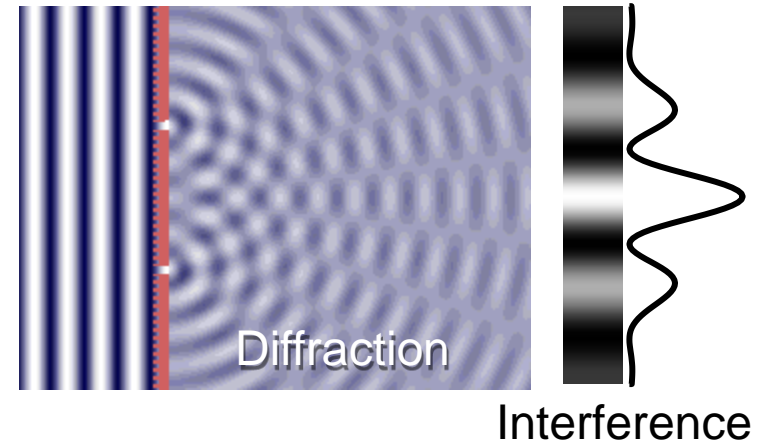
Newton

Huygens / Maxwell

Particle / Photon



Wave (electromagnetic ~)



Wave – Particle Dualism

Here: consider light as electromagnetic wave

Maxwell's Equations

Time domain:

$$\nabla \times \vec{E}(\vec{r}, t) = -\frac{\partial}{\partial t} \vec{B}(\vec{r}, t)$$
$$\nabla \times \vec{H}(\vec{r}, t) = j(\vec{r}, t) + \frac{\partial}{\partial t} \vec{D}(\vec{r}, t)$$
$$\nabla \cdot \vec{D}(\vec{r}, t) = \rho(\vec{r}, t)$$
$$\nabla \cdot \vec{B}(\vec{r}, t) = 0$$

$\vec{E}(\vec{r}, t)$... electric field
 $\vec{B}(\vec{r}, t)$... magn. induction
 $\vec{H}(\vec{r}, t)$... magn. field
 $\vec{D}(\vec{r}, t)$... dielectric displacement
 $j(\vec{r}, t)$... current density
 $\rho(\vec{r}, t)$... charge density

linear matter equations:

$$j(\vec{r}, t) = \sigma \cdot \vec{E}(\vec{r}, t)$$
$$\vec{D}(\vec{r}, \omega) = \varepsilon_0 \varepsilon_r(\omega) \vec{E}(\vec{r}, \omega)$$
$$\vec{B}(\vec{r}, \omega) = \mu_0 \mu_r(\omega) \vec{H}(\vec{r}, \omega)$$

(frequency domain)

σ ... conductivity

Wave Equation

Linear, homogeneous, isotropic medium, no free charges:

$$\nabla^2 \vec{E}(\vec{r}, t) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \vec{E}(\vec{r}, t) = 0 \quad (1.1)$$

Wave equation for the electric field $\vec{E}(\vec{r}, t)$

c ... velocity of light in the medium

c_0 ... velocity of light in vacuum

$$c = \frac{c_0}{\sqrt{\epsilon\mu}} = \frac{c_0}{n}$$

One solution of this equation:

$$\vec{E}(\vec{r}, t) = \vec{E}(\vec{r}) \cdot e^{-i\omega t} \quad (1.2)$$

→ field with harmonic time dependence

$$\omega = 2\pi f$$

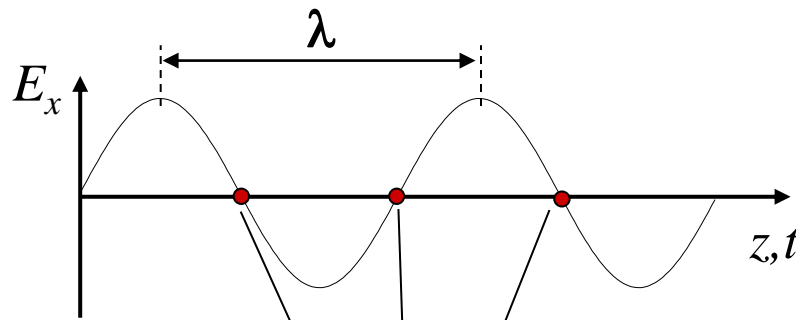
f ... time frequency of oscillation

Light as a harmonic wave

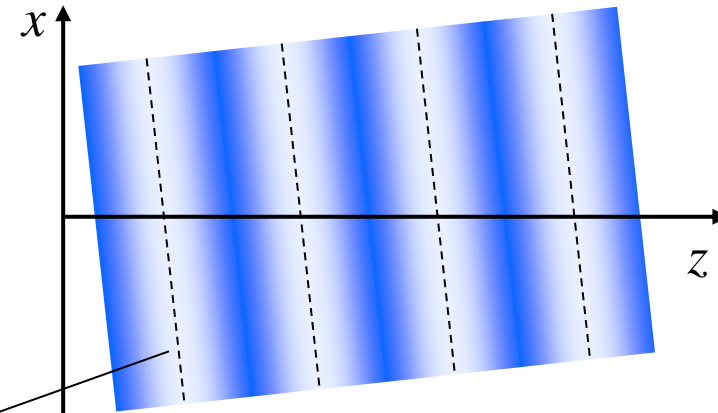
1D Representation:

$$\vec{E} = \vec{A} \cdot \cos \left[\underbrace{2\pi \cdot \left(f \cdot t - \frac{z}{\lambda} \right)}_{\text{Phase}} \right]$$

$$f = \frac{c}{\lambda} \quad \text{Frequency} \rightarrow \text{Color}$$



2D:



Points / Lines of equal phase \rightarrow **Wave-Fronts!**

Time-free wave equation

inserting (1.1) in (1.2) leads to the simplification

$$\nabla^2 \vec{E}(\vec{r}) + \frac{\omega^2}{c^2} \vec{E}(\vec{r}) = 0 \quad (1.3)$$

 **Helmholtz - Equation**

$$\frac{\omega^2}{c^2} = k^2 = \left(\frac{2\pi}{\lambda} \right)^2$$

k ... modulus of the k-vector

Fundamental solutions of Helmholtz's Equation, I

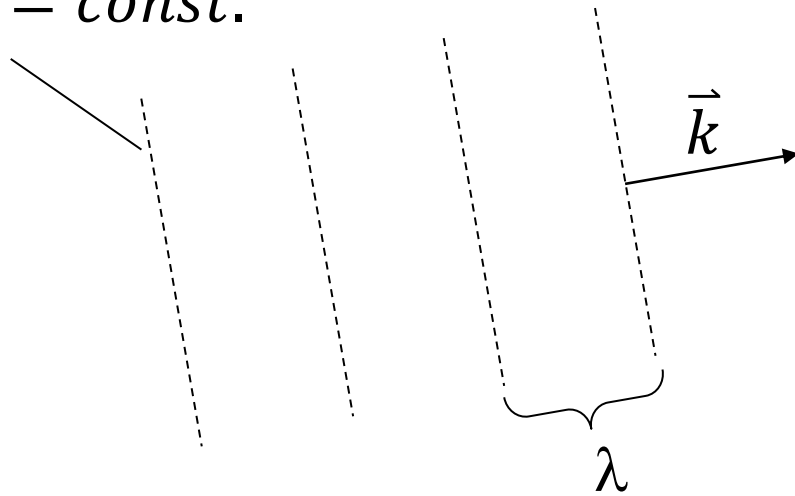
First basic solution of (1.3):

$$\vec{E}(\vec{r}) = \vec{E}_0 \cdot e^{i\vec{k} \cdot \vec{r}} = \vec{E}_0 \cdot e^{i\varphi} \quad (1.4)$$

$$\varphi = \vec{k} \cdot \vec{r}$$

→ equation describing a plane

$\varphi = \text{const.}$



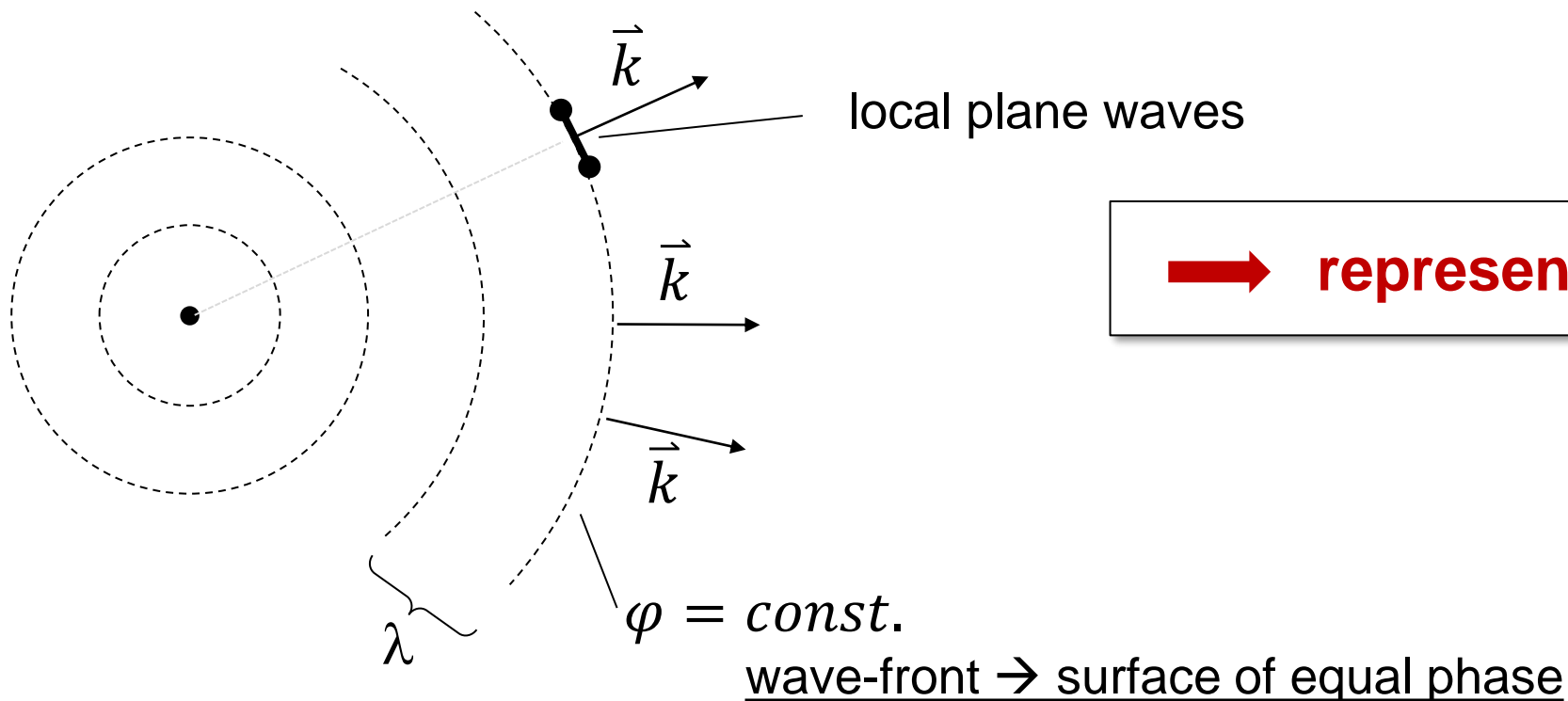
→ plane wave (propagating in direction of \vec{k})

Fundamental solutions of Helmholtz's Equation, II

Second basic solution of (1.3):

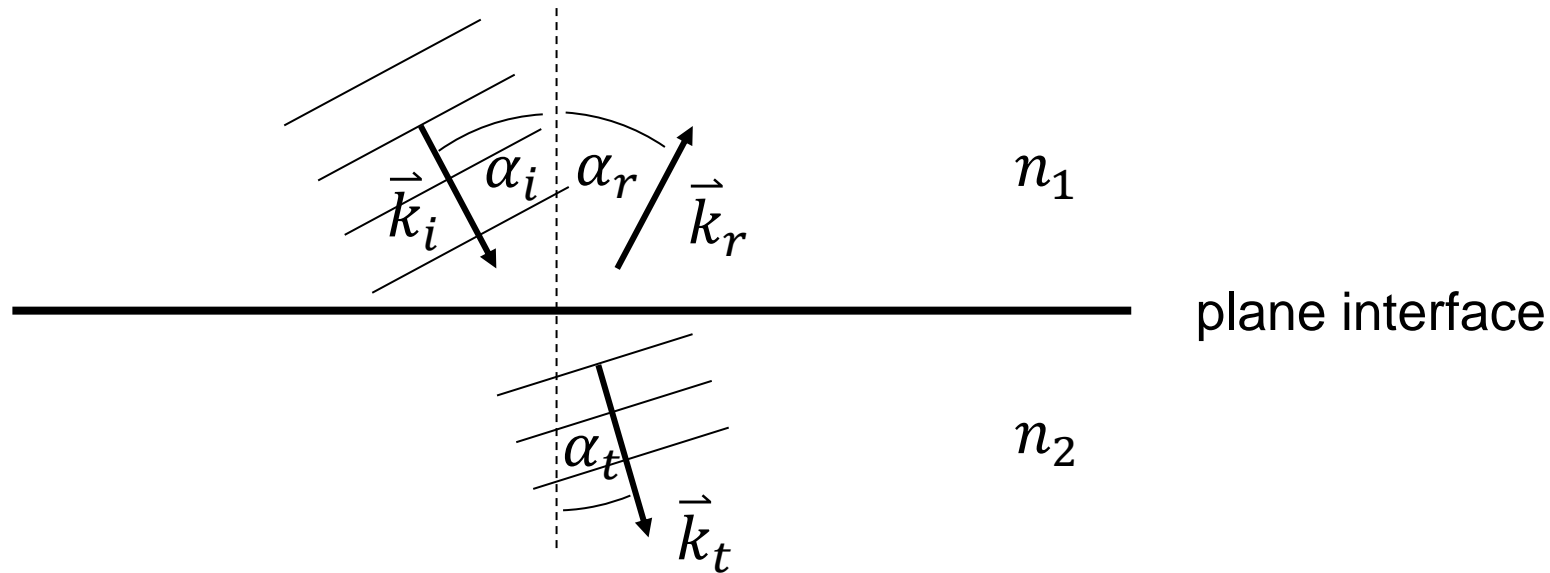
$$E(\vec{r}) = \frac{E_0}{r} \cdot e^{ik \cdot r} \quad (1.5)$$

→ spherical wave (from a point source)



1.2 Interaction of light with plane interfaces

consider a plane wave with propagation direction \vec{k}



Symmetry:

only 3 waves present

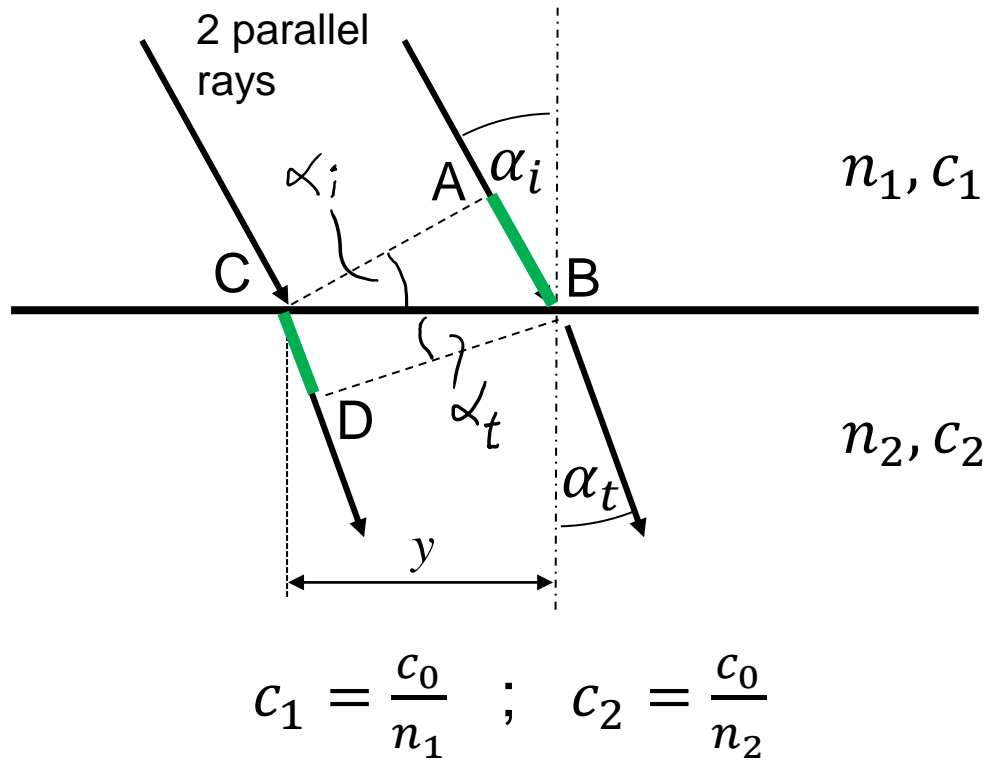
- incident field, direction \vec{k}_i , α_i to surface normal
- transmitted field, direction \vec{k}_t , α_t to surface normal
- reflected field, direction \vec{k}_r , α_r to surface normal

} **all plane waves**

Relation between the α and distribution of energy among the waves ➡ **Fresnel's formulas**

The Transmitted Wave

using a different model, based on a **consideration of travelling speeds** of rays in the different media



incident plane wave \rightarrow transmitted plane wave

\rightarrow same travelling time $A \rightarrow B$
 $C \rightarrow D$

$$t = \frac{y \cdot \sin \alpha_i}{c_1} = \frac{y \cdot \sin \alpha_t}{c_2}$$

$$n_1 \cdot \sin \alpha_i = n_2 \cdot \sin \alpha_t \quad (1.6)$$

law of refraction, Snell's law

Similar consideration for reflected wave:

$$\alpha_i = \alpha_r$$

law of reflection

(1.7)