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## ► To cite this version:

Arthur Gautheron, Raphaël Clerc, Vincent Duveiller, Lionel Simonot, Bruno Montcel, et al.. How much light is internally reflected at the boundaries of translucent layers ?. Sleight Science Event #8 - Photonics for health, Jul 2022, Saint-Etienne, France. hal-03716087

**HAL Id: hal-03716087**

**<https://hal.science/hal-03716087>**

Submitted on 7 Jul 2022

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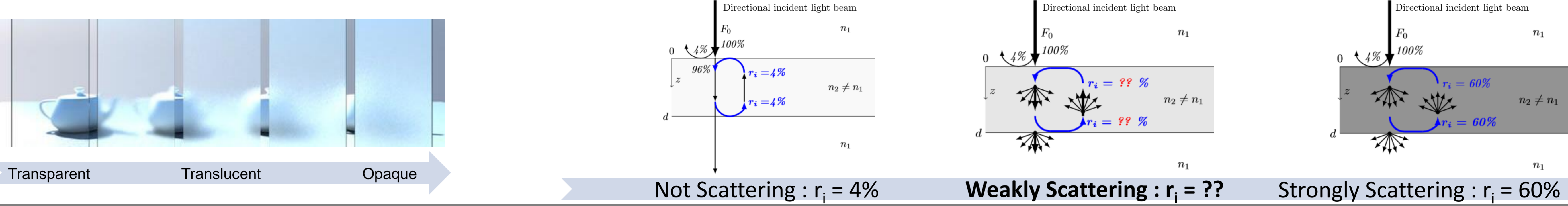
# How much light is internally reflected at the boundaries of translucent layers ?

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## Between transparent and opaque : translucent material.

In a **transparent medium**, a **directional beam remains directional**. In an **opaque diffusing layer**, the **directional beam becomes perfectly diffused**. In **translucent layers**, the **directional beam is scattered progressively** along its path.  
At the bordering interfaces of a layer of material, some light is internally reflected and goes back into the layer. The **fraction of internally reflected light** (represented by parameter  $r_i$ ) strongly **depends** onto **the angular distribution of the scattered light**, with respect to the Fresnel reflectance formulae. The main insight of this work is to show that the amount internally reflected light is not the same at the two boundaries, and it depends a lot on the thickness of the layer.

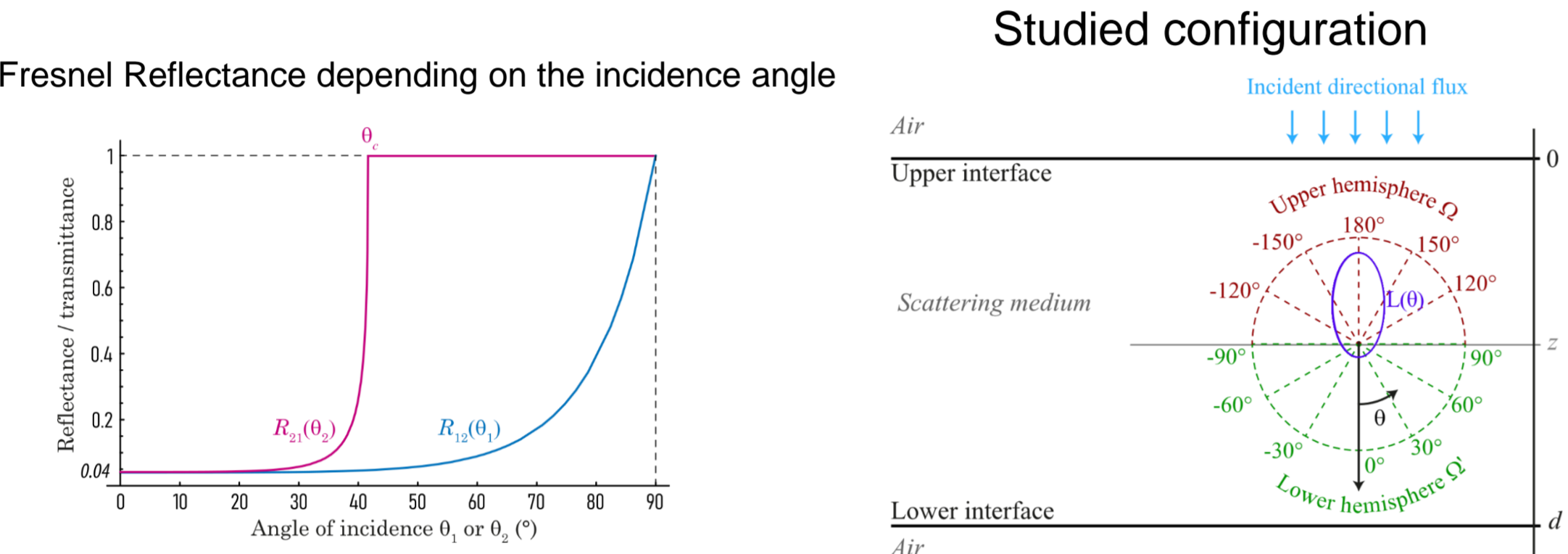


Not Scattering :  $r_i = 4\%$       Weakly Scattering :  $r_i = ??$       Strongly Scattering :  $r_i = 60\%$

## Methods

### Solving the radiative transfer equation with bordering interfaces

To **determine** the fraction of **internally reflected light**,  $r_i$ , we **need to know** the **angular distribution** of light **at the interface**. For this, we will **estimate** it through a model of light scattering, **by solving the RTE**, finite element method.  
The main parameters are: optical index  $n$ , absorption coefficient  $k$ , scattering coefficient  $s$ , anisotropy parameter  $g$ , etc. Another important parameter, little known, is the thickness  $d$  of the layer.



- Assumptions :
- Incident directional flux at normal incidence on the whole surface, featuring an azimuthal symmetry.
  - 1D geometry : physical quantities only depend on the depth  $z$  and zenithal angle  $\theta$ .
  - Internal reflections at both sides of the directional light component

Radiative Transfer Equation solved using Discrete Ordinates Method [5]

$$\mu \frac{dL}{d\tau}(\tau, \mu) = -L(\tau, \mu) + \frac{1}{2} \int_{-1}^1 p_0(\mu, \mu') L(\tau, \mu') d\mu'$$

Boundary Conditions at both interfaces include Fresnel reflections

$L$	Radiance ( $\text{Wm}^{-2}\text{sr}^{-1}$ )	$\tau$	Optical Thickness ( $\tau = (\mu_s + \mu_a)z$ where $z$ is the depth of interest in cm)
$\mu_a$	Absorption coefficient ( $\text{cm}^{-1}$ )	$\omega_0$	Albedo of the sample with $\omega_0 = \mu_s / (\mu_s + \mu_a)$
$\mu_s$	Reduced scattering coefficient ( $\text{cm}^{-1}$ )	$p_0$	Phase Function partially integrated
$\mu$	cosine of the interest angle $\theta$		

### Diffuse Internal Reflectance

$$r_{id} = \frac{\int_0^{\pi/2} L_0(\pi - \theta) R_{21}(\theta) \sin(2\theta) d\theta}{\int_0^{\pi/2} L_0(\pi - \theta) \sin(2\theta) d\theta}$$

Similar formula for  $r'_{id}$  at bottom interface

### Global Internal Reflectance

$$\text{Top Interface } r_{ig} = \frac{F_d}{F_d + F_N} r_{id} + \frac{F_N}{F_d + F_N} r_N$$

$$\text{Bottom Interface } r'_{ig} = \frac{F'_d}{F'_d + F'_N} r'_{id} + \frac{F'_N}{F'_d + F'_N} r'_N$$

$F_d$  Diffused Flux  
 $F_N$  Directional Flux  
 $r_N$  Fresnel reflectance at normal incidence from the medium through air.  
 $x'$  Quantity referring to the bottom interface.

### Validity of the 2- and 4-flux models with and without internal reflectance

Reflectance & Transmittance generated with RTE Solver for various thicknesses

Extraction of optical parameters with 4-flux RTE Model for a given thickness

Optical Parameters  
Absorption coefficient  $k$ ,  
scattering coefficient  $s$

Conversion to 2-flux optical parameters  
Absorption coefficient  $k$ , scattering coefficient  $S$  of the Kubelka-Munk model

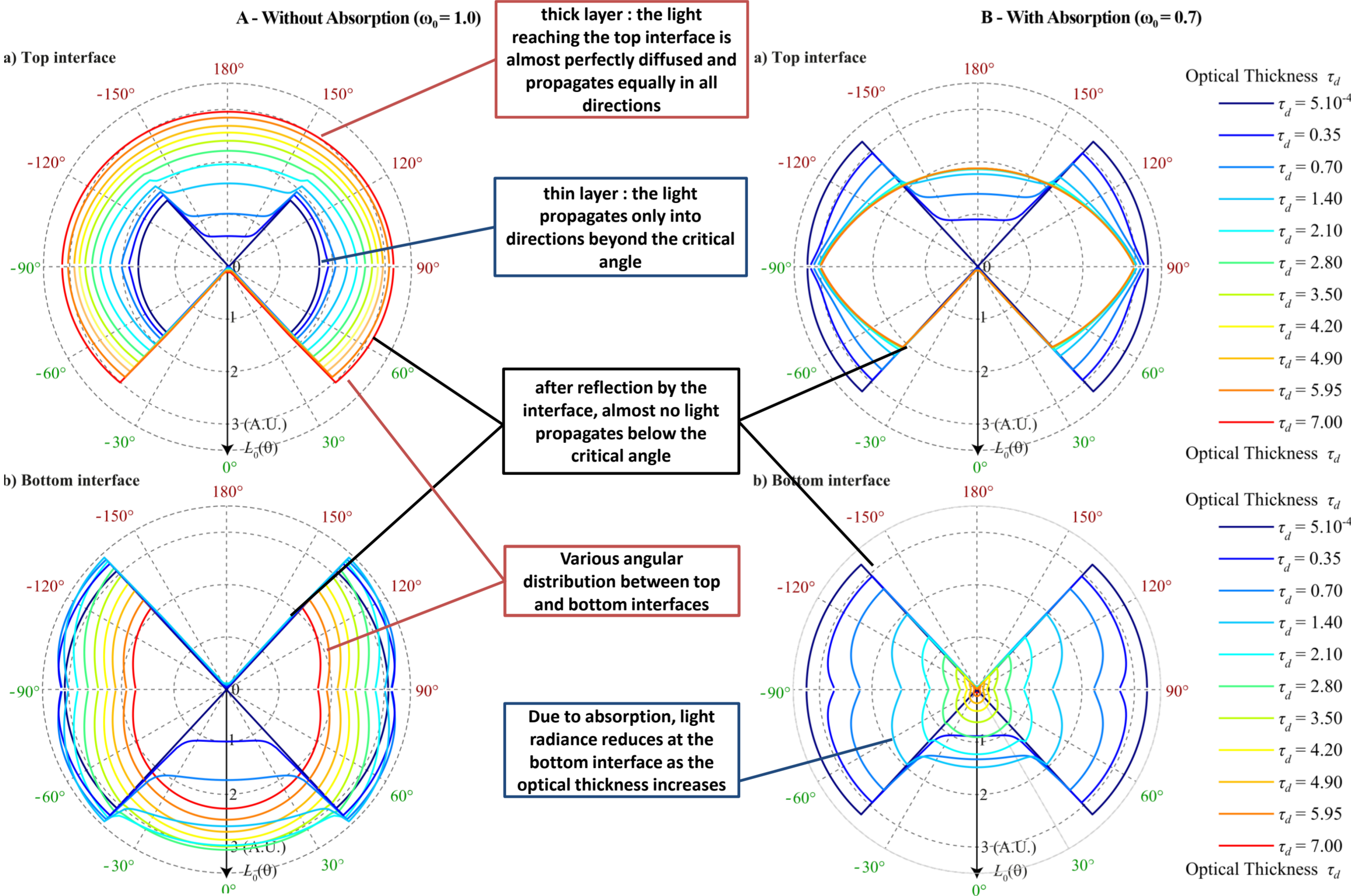
Reflectance & Transmittance generated by each 4-flux model ( $r_i$  60%,  $r_i$  RTE)

Reflectance & Transmittance generated by each 2-flux model ( $r_i$  0%,  $r_i$  4%,  $r_i$  60%,  $r_i$  RTE)

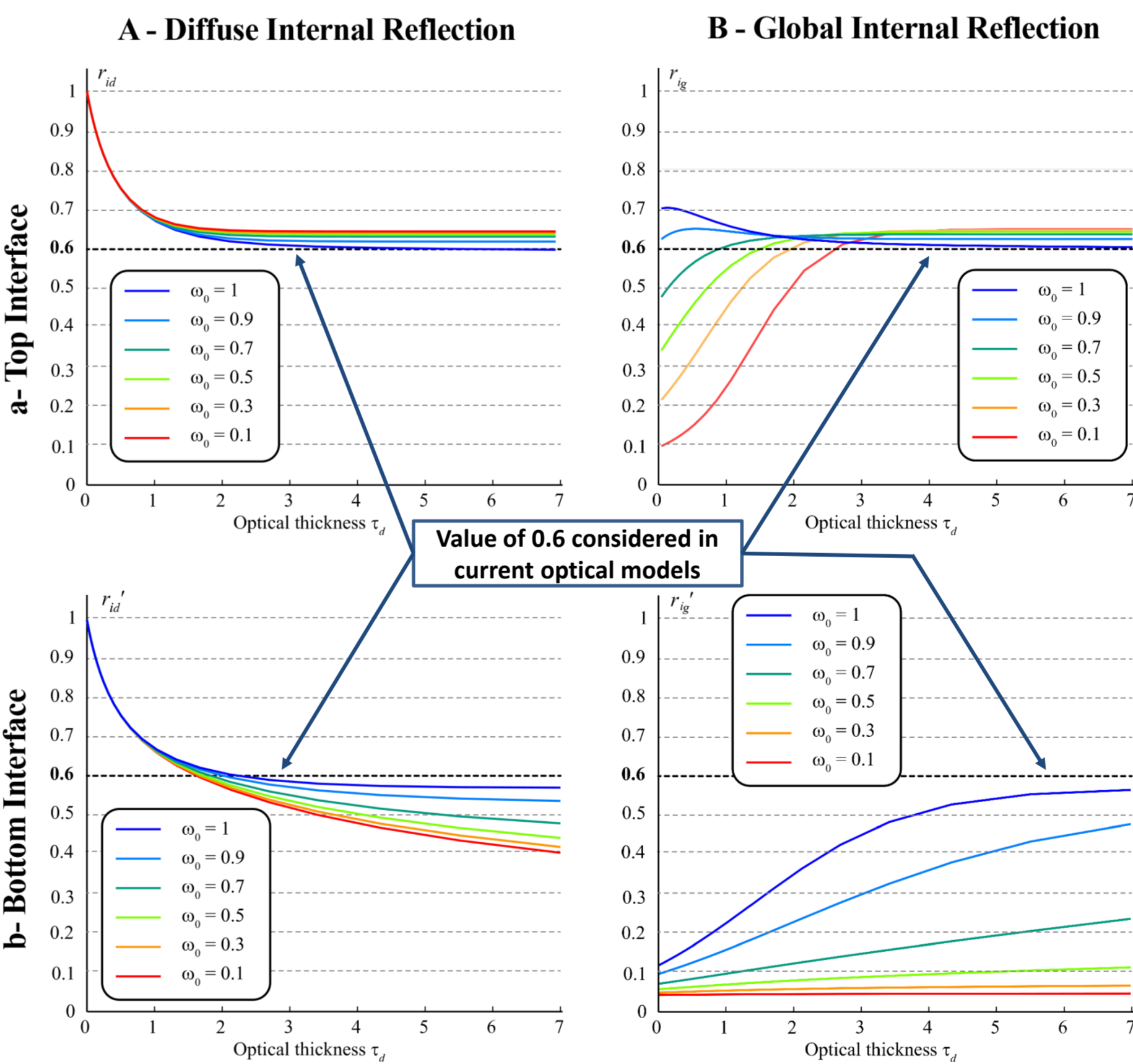
Comparison with Ground Truth

## Results and Discussion

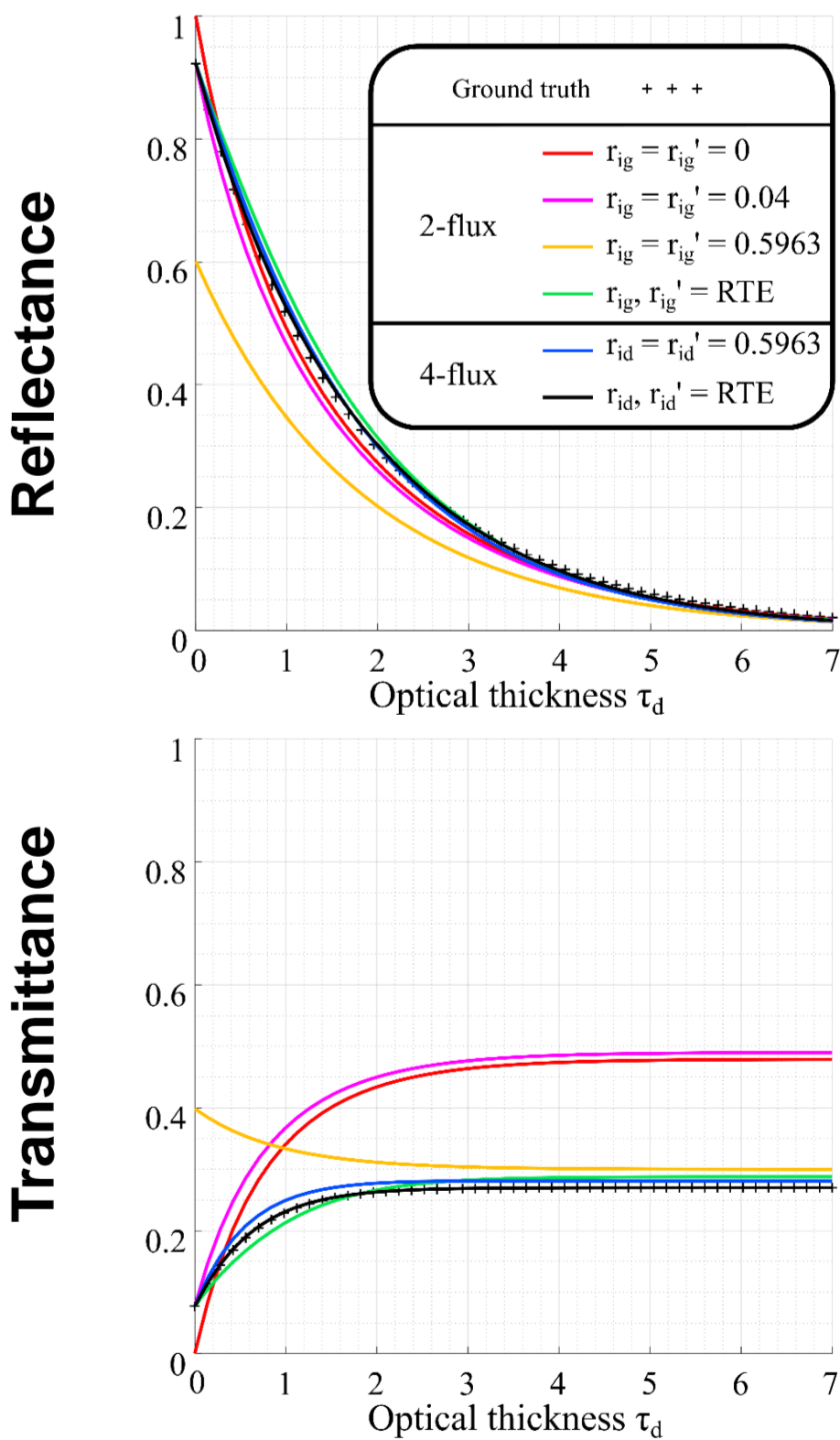
### Angular Distributions of Scattered Light



### Evolution of internal reflectance



### Validity of the 2- and 4-flux models with and without internal reflectance



- Internal reflectance equal to its **Lambertian light** can **lead to significant errors** (up to 100%) for 2-flux models when dealing with translucent materials.
- The **internal reflectance** value **varies** a lot with optical thickness and absorption.
- Parameter extraction** with 2- and 4-flux models can be **significantly improved** using the internal coefficient calculated using the radiative transfer equation.

A full description and results of this study are described in [4] and an Optic Express article.

## Acknowledgments

This work has been funded by LABEX PRIMES (ANR-11-LABX-0063) of Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR) and carried out within the framework of France Life Imaging (ANR-11-INBS-0006).

It has also supported by a public grant from the French National Research Agency (ANR) under the Investments for the Future Program (PIA), which has the reference EUR MANUTECH SLEIGHT ANR-17-EURE-0026.

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## Perspectives

- Lookup Table creation to optimize parameters extraction with Kubelka-Munk and Diffusion Approximation Models
- Evaluation of its impact on the estimation of chromophore concentration in biological tissues
- Evaluation of its impact on the measurement correction due to biological tissues

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