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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 ?

Arthur Gautheron^{1,2}, Raphaël Clerc², Vincent Duveiller², Lionel Simonot³, Bruno Montcel¹ and Mathieu Hébert²

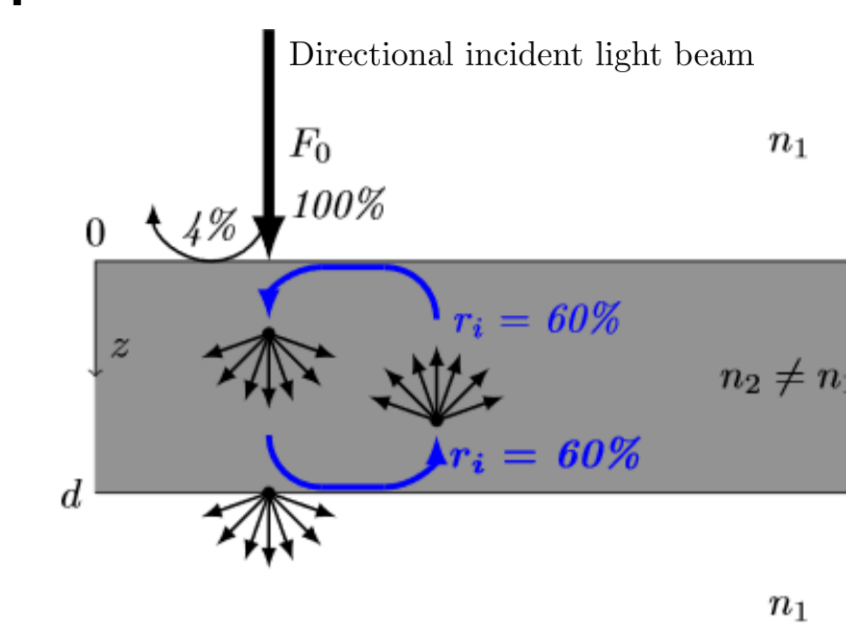
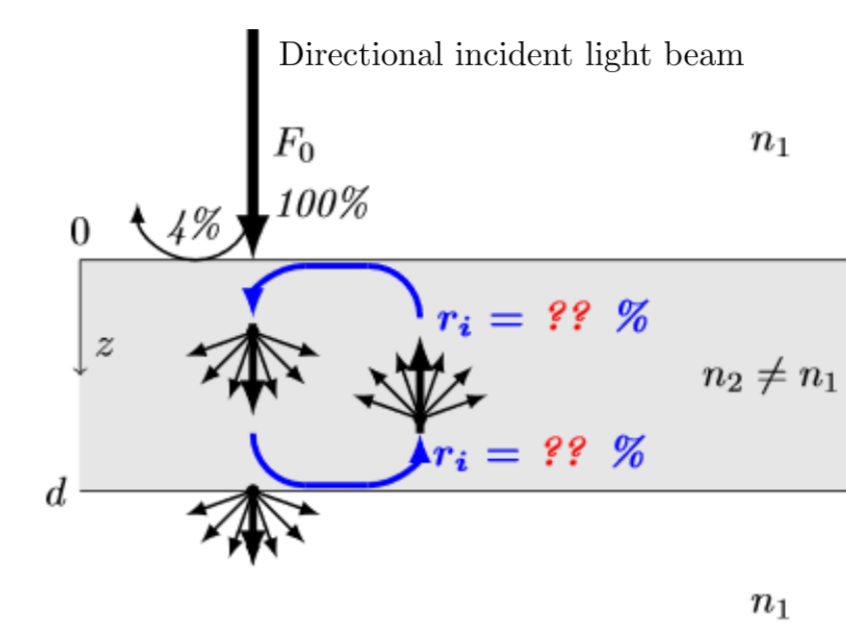
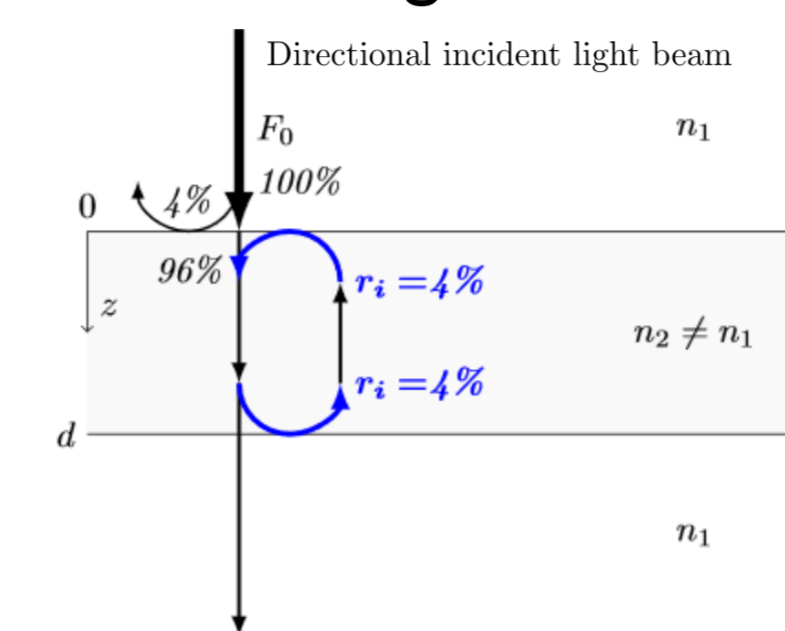
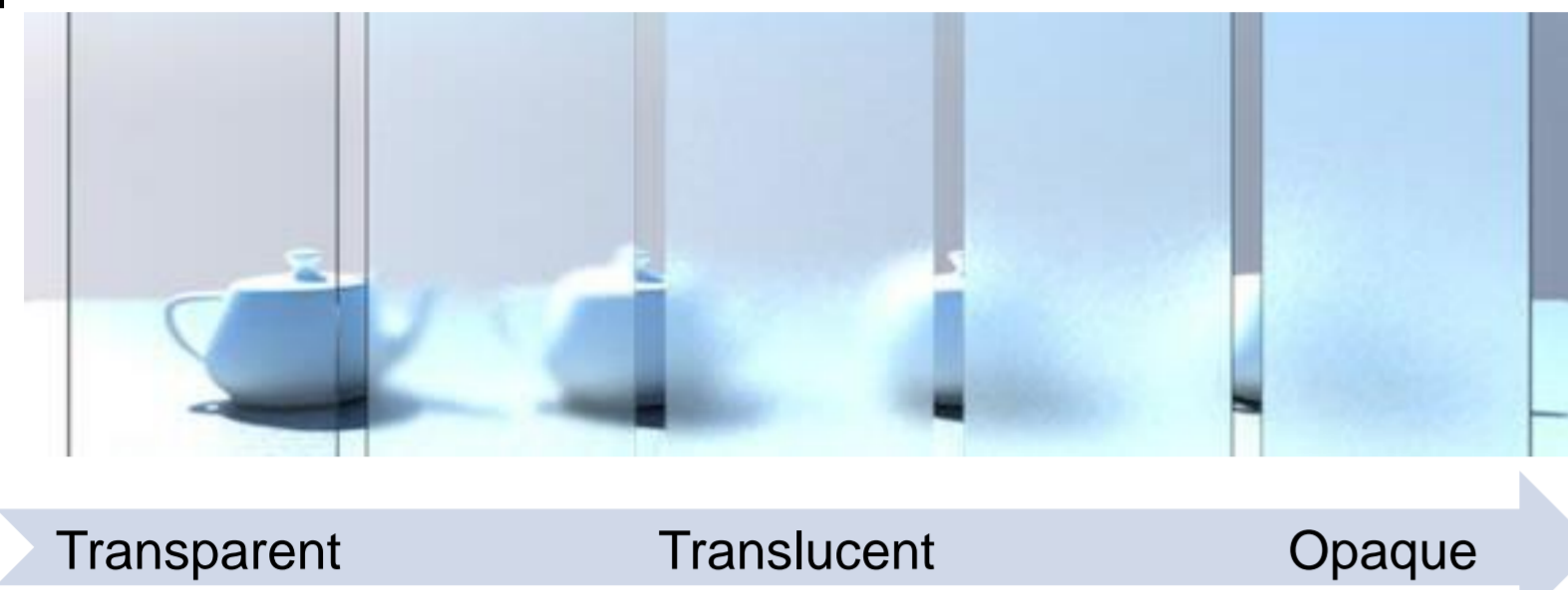
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Between transparent and opaque : translucent material.

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 : $r_i = ??$

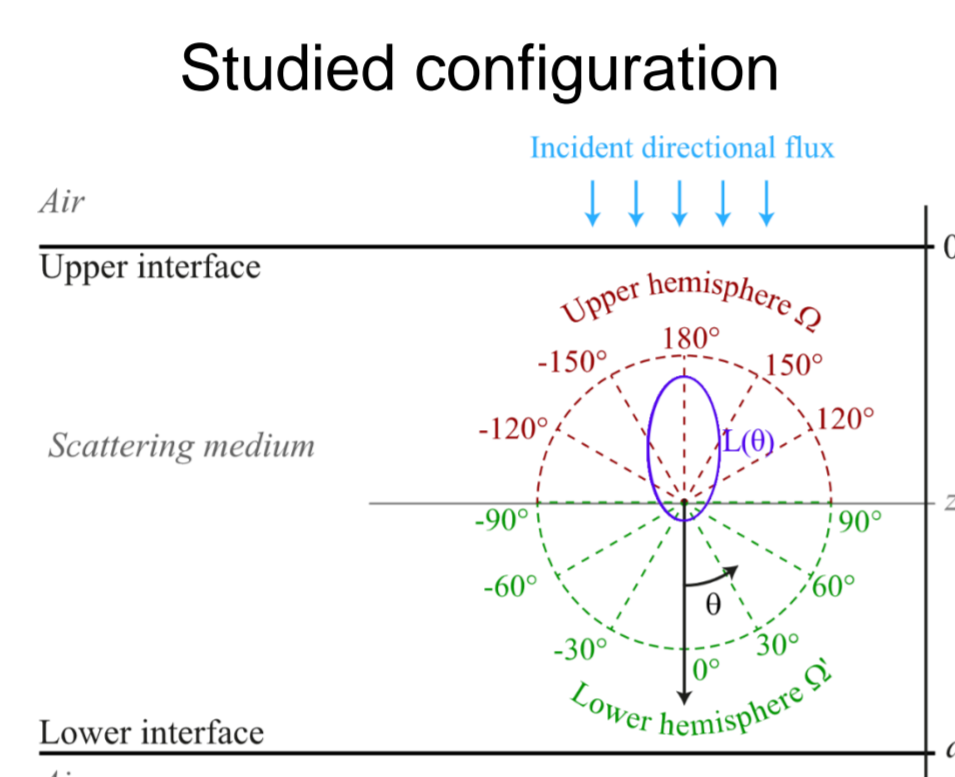
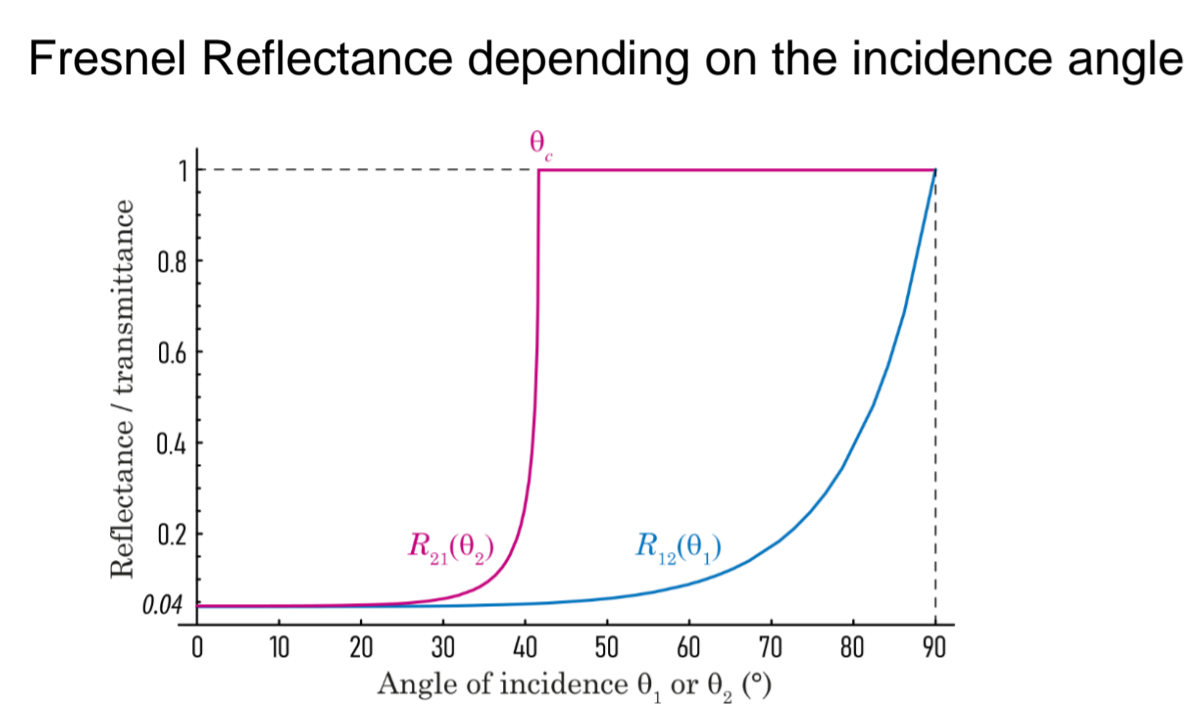
Strongly Scattering : $r_i = 60\%$

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.



Angular Distribution of light

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

- 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 θ .
 - Internal reflections at both sides of the directional light component

Radiative Transfer Equation solved using Discrete Ordinates Method [5]

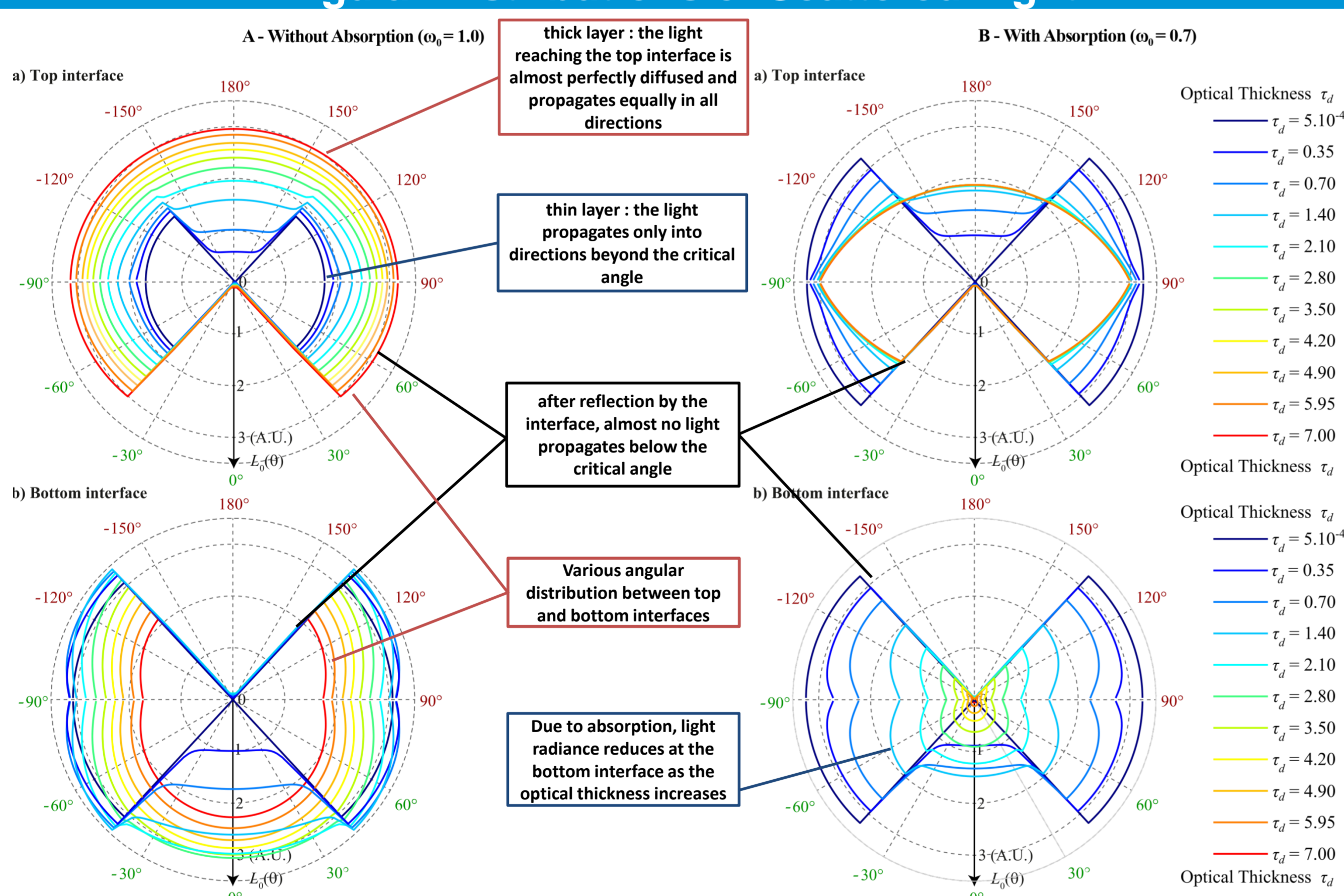
$$\mu \frac{dL}{d\tau}(\tau, \mu) = -L(\tau, \mu) + \frac{1}{2} \int_{-1}^1 p_0(\mu, \mu') L(\tau, \mu') d\mu'$$

Boundary Conditions at both interfaces include Fresnel reflections

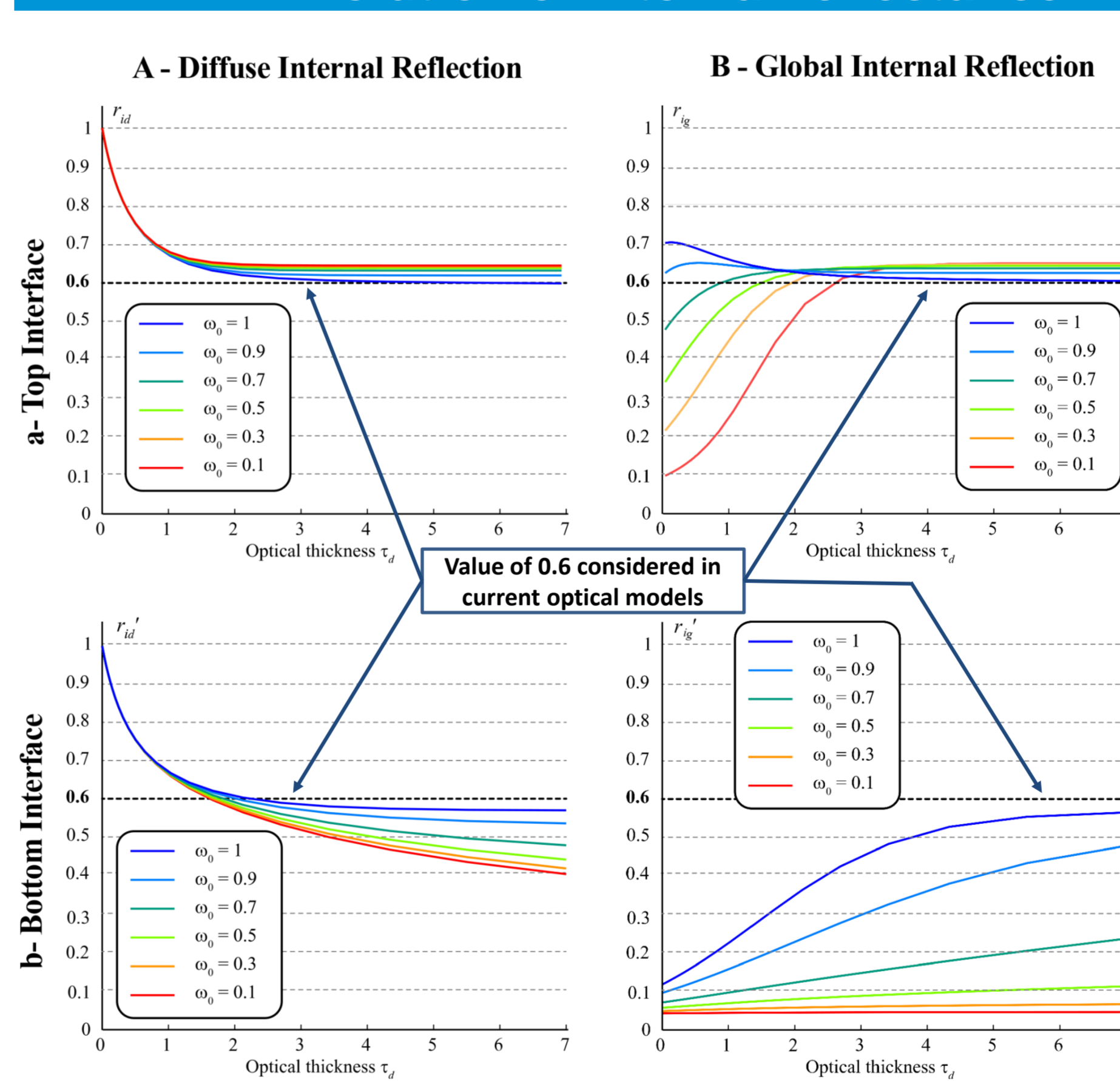
L	Radiance ($\text{Wm}^{-2}\text{sr}^{-1}$)	τ	Optical Thickness ($\tau = (\mu_s + \mu_a)z$ where z is the depth of interest in cm)
μ_a	Absorption coefficient (cm^{-1})	ω_0	Albedo of the sample with $\omega_0 = \mu_s / (\mu_s + \mu_a)$
μ_s	Reduced scattering coefficient (cm^{-1})	p_0	Phase Function partially integrated
μ	cosine of the interest angle θ		

Results and Discussion

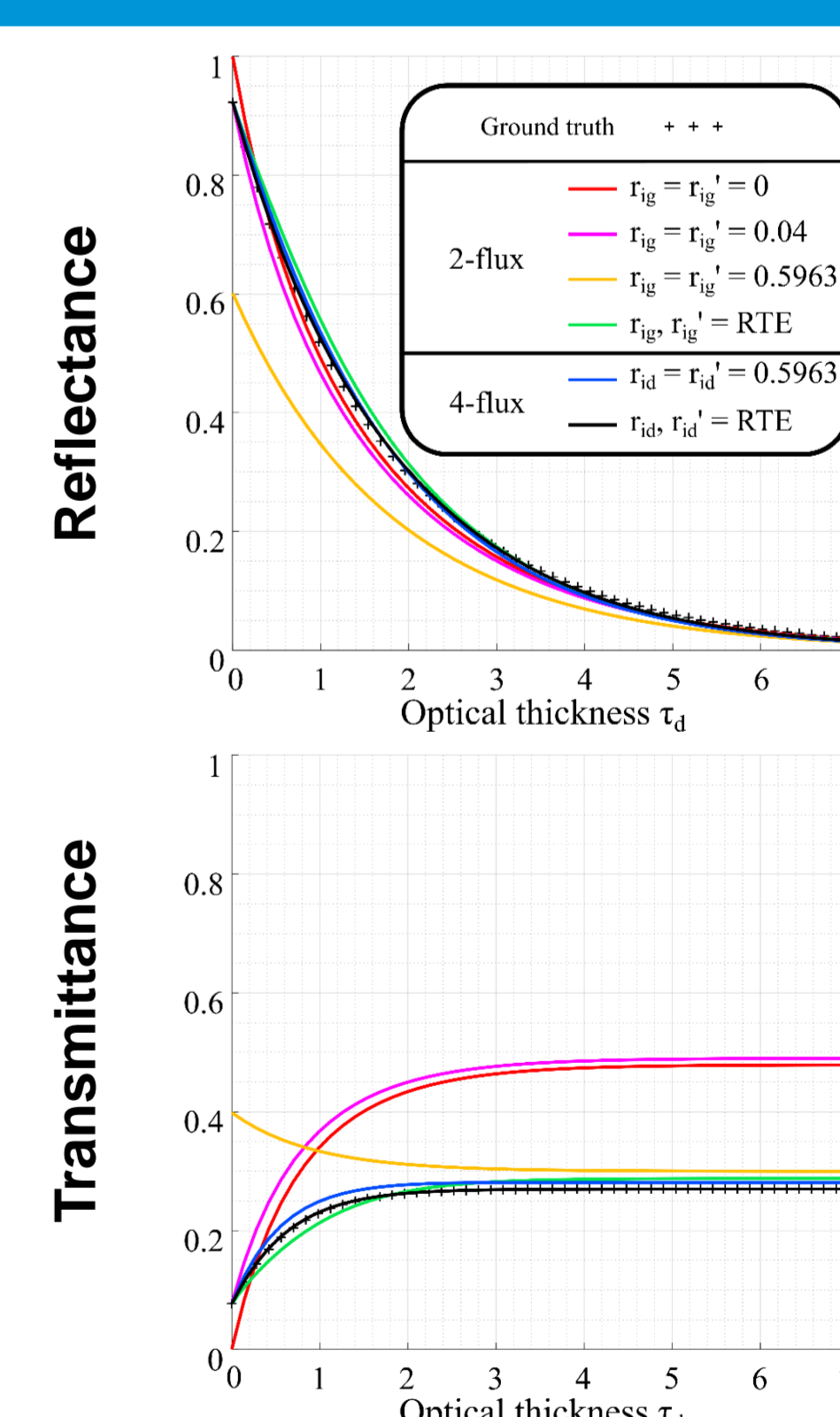
Angular Distributions of Scattered Light



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

[1] Kubelka P. et al., Ein Beitrag zur Optik der Farbanstriche (1931).
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[3] Saunderson L., Journal Optical Society of America 32, p. 727-736 (1942)
[4] Gautheron A. et al. Proc. Symp. on Electronic Imaging: Color Imaging: Displaying, Processing, Hardcopy, and Applications, pp 221-1 - 221-6 (2022)
[5] Ishimaru A., Wave propagation and scattering in random media, vol 2, (1978)

