Photonic Rendering for Hair Cuticles using High Accuracy NS-FDTD method

Zhuo Hou
University of Tsukuba
Japan
hou@cavelab.cs.tsukuba.ac.jp

Dongsheng Cai
University of Tsukuba
Japan
cai@cs.tsukuba.ac.jp

Ran Dong
Tokyo University of Technology
Japan
randong@stf.teu.ac.jp

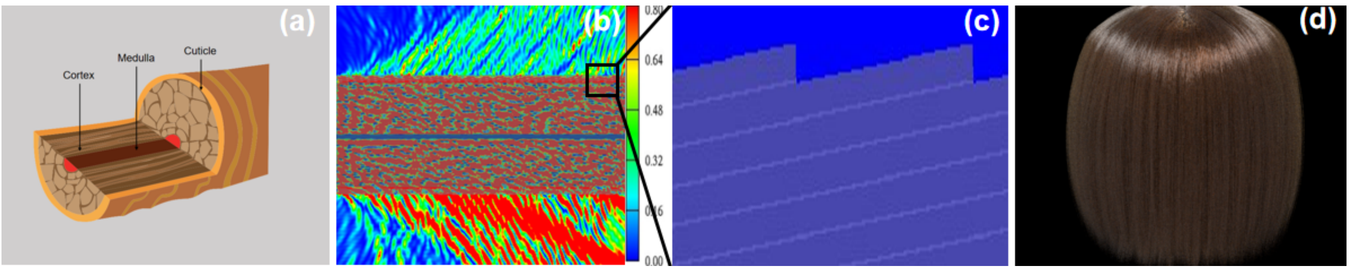

Figure 1: (a) Microstructure of hair. (b) Snapshot of hair model optical simulation using NS-FDTD[Cole 2005] method, the simulation model includes the necessary parts of the hair: cuticle, medulla, and cortex containing melanin pigment. Color bars indicate the reflectance ratio. And figure(c) shows the cuticle in the microscopic view of our simulation. (d) Photonic rendering for a hair fiber using NS-FDTD method.

ABSTRACT

The internal structure of hair consists of three layers: the cuticle, the cortex, and the medulla, and there are multiple membrane structures inside the cuticle. Light incident on these subwavelength structures is subject to scattering and interference phenomena, and the reflected highlights vary depending on the viewing angle. This phenomenon of light coloration due to the microstructure is called structural coloring or photonic coloration. It shows a unique specular highlight and determines the magnitude of the specular highlight, which is not observable in the linear optics of CG. In the case of hairs, this structural coloring or photonic coloration occurs in addition to the simple surface reflections and the backscattering lights, which penetrate the hair and are absorbed by the melanin pigment. In the present report, we mainly discuss the effects of the structural coloring first caused by the multi-layered structure in the cuticle region on the hair surface, simulating the electromagnetic field using the NS-FDTD (Non-Standard Finite Difference in Time Domain) method. In addition, we also discuss the backscattering phenomena inside the hair fibers.

CCS CONCEPTS

• **Computing methodologies → Reflectance modeling**.

KEYWORDS

numerical simulation, rendering, computer graphics, structural coloring

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1 INTRODUCTION

When we focus on the surface and internal structure of the hair at the nanoscale, the micro-structure repeatedly undergoes light interference and scattering phenomena, and the colors generated by scattering and interference give a unique visual effect, so-called structural coloring or photonic coloration. In most cases, rendering methods and theoretical calculations used in conventional CG images consider only two elements, surface reflected lights and backscattering lights. However, due to the nature of the complex phenomenon of light scattering, only part of these effects can be obtained in a usual CG modeling. In the present paper, we discuss their significance and impacts of these micro-structures of hair in CG modeling.

2 NS-FDTD ELECTROMAGNETIC SIMULATION

The FDTD (Finite difference time-domain) method was proposed by Yee[Yee 1966] as a method for the numerical simulation of electromagnetic fields, which solves the differential equations by substituting a difference operator and discretizes the domain. Generally, the FDTD using Yee's grid has lower accuracy. Because of the limitation of computing resources, using a higher precision grid will

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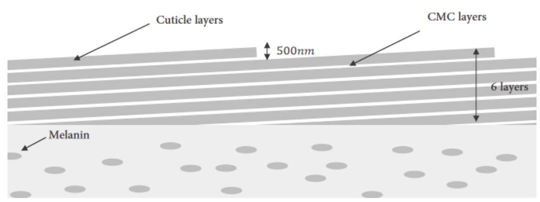

Figure 2: The cuticle structure of the hair. The cuticle layers cover the surface of the hair. Each cuticle layer is in turn composed of organic layers such as CMC and lipids.

significantly increase calculation. We introduced a second-order FDTD algorithm called Non-Standard FDTD(NS-FDTD) algorithms to solve Maxwell's equations.

3 CUTICLE MODEL FOR NS-FDTD SIMULATION

The figure 1(a) shows that the human hair is composed of three tissues: the scaly cuticle covering the surface, the fibrous cortex containing melanin pigment, and the medulla that constitutes a hair axis in the center.

As shown in Figure 2, the cuticle, located at the top surface of the hair, is a transparent, plate-like cell about 0.5 μm thick, with a layered structure consisting of about 6 to 10 overlapping layers like roof tiles. The angle of inclination is about 2 to 5 degrees. In addition, there is a cell membrane complex (CMC) with a thickness of about 25*nm* between the layers of cuticle cells, which serves as a pathway for substances to penetrate the hair. The hair cuticle structure is a multilayer structure, and it undergoes many interferences and scattering phenomena. It is known to be essential for rendering hair images to simulate the structural coloring or photonic coloration produced by these phenomena.

4 LONGITUDINAL SCATTERING FROM INTERNAL HAIR FIBER

Simulating or modeling the reflected light from a hair is crucial for hair renderings. Marschner et al. [Marschner et al. 2003] proposed a physiological structure-based reflectance model that significantly improves the accuracy of light reflectance by calculating the transmission path of light inside the hair, which is still the mainstream of hair rendering methods nowadays. However, the presence of internal melanin and external cuticle multi-layers on the hair is not considered, and only a part of the internal refraction was calculated. Our method tries to capture the light that passes through inside hair, including the cuticle, cortex, and medulla.

As shown in Figure 3, T and R, respectively, stand for the transmission and reflection across the hair's surface. In natural light propagation, hair creates many path patterns such as R, TT, TRT, etc. Capturing as many reflected lights as possible is one of the keys to enhancing visual effects. Applying the NS-FDTD method to simulate the electromagnetic waves coming into the interior of the hair can reproduce the actual intensity of the reflected light as much as possible. The hair rendering pipeline was (1) modeled on a nanoscale structure based on transmission electron microscopy

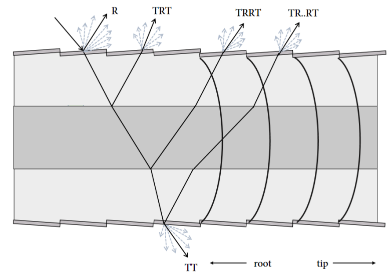

Figure 3: Refection and Transmission mode through hair fiber. T and R stand for transmission and reflection, respectively, across a hair fiber.

images. (2) Simulate the longitudinal scattering of the hair cuticle using the NS-FDTD method. (3) Rendering the hair image based on the BSDF (Bidirectional Scattering Distribution Function) method. In the rendering process, we replace the longitudinal scattering function in BSDF with the scattering intensity function simulated by the NS-FDTD method. Then, this function is integrated into the PBRT-v3[Pharr et al. 2016] renderer by introducing a hair material[Bitterli 2016] .

In our simulation, we first solve the complete form of Maxwell's equations by simulating the near-field reflections of whole hair fiber in transverse electric (TE) and transverse magnetic (TM) modes. The computational domain is terminated by a non-standard perfectly matched layer absorption boundary condition. Since the Longitudinal scattering reflectance is measured in the far field, we use the near-field to far-field conversion to obtain the far-field reflectance distribution. This simulation is repeated for each wavelength range from 380nm to 700nm. Figure 1(b) shows simulated snapshots at an incident light angle of 60°and Figure 1(c) shows the cuticle in the microscopic view of our simulation. Finally, the CG rendering results are shown in Figure 1(d).

5 CONCLUSIONS

In the present talk, we use the NS-FDTD method to simulate the electromagnetic field for the nano-scale structure of the hair fiber. We show that the structural coloring due to the multilayered structure appears in the cuticle region of the hair surface using the NS-FDTD method. Our photonic rendering results show that the complicated hair colors and visual effects are successfully reproduced and rendered as a CG image. However, these have to be carefully compared with real hair images under different conditions such as wet, dry, damaged, curled hairs.

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