

Numerical Simulation of the Interaction between Electromagnetic Waves and Anisotropic Media in the Eye with the Finite-Difference Time-Domain Method

Mario Angel Rico-Mendez ^{1, 2}, Norma Patricia Puente-Ramirez ², and Romeo Selvas ¹

¹Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Nuevo León, 66455 San Nicolás de los Garza, México

²Facultad de Ingeniería Mecánica y Eléctrica, Universidad Autónoma de Nuevo León, 66455 San Nicolás de los Garza, México

The interaction of light with the human eye is a complex phenomenon that involves both visual and non-visual pathways, serving essential roles in various physiological and psychological processes. In this study, we employ the Finite-Difference Time-Domain (FDTD) method, an advanced numerical technique for solving Maxwell's equations across both temporal and spatial domains, facilitating a precise simulation of the interaction between electromagnetic waves and the heterogeneous and anisotropic media of the eye. The results are anticipated to offer significant insights into the variations in energy distribution patterns and their potential implications for the safety and efficacy of optical applications.

Index Terms—Electromagnetic wave analysis, Human eye, Numerical modeling.

I. INTRODUCTION

THE INTERACTION of light with the human eye is a complex phenomenon that involves both visual and non-visual pathways, serving essential roles in various physiological and psychological processes. Comprehending the propagation of light of diverse wavelengths through the ocular system is integral to elucidating the performance of optical systems, assessing risks to ocular health, and informing the design of laser-based medical apparatuses. The primary mechanism of light perception begins with the photoreceptor cells in the retina, which include rods, cones, and intrinsically photosensitive retinal ganglion cells (ipRGC). The photoreceptor cells react to light stimuli by producing electrical signals, which are conveyed via the optic nerve to the visual cortex. Here, visual information undergoes processing and interpretation [1], [2].

Rods and cones are responsible for image-forming vision, allowing humans to perceive a limited spectrum of light, specifically between 380 and 780 nm [3]. Nevertheless, the function of ipRGC surpasses simple image formation, as they are essential to non-visual photoreception. They play a critical role in modulating circadian rhythms and hormonal regulation, notably in the inhibition of melatonin synthesis upon exposure to light [4], [5].

Short laser pulses, especially within the visible and near-infrared spectrum, are commonly utilized in diverse medical applications, including refractive surgery and diagnostic imaging. However, the energy distribution and propagation characteristics of these pulses vary significantly depending on the wavelength. This investigation is centered on the comparison of propagation and energy concentration between 450 nm and 750 nm wavelengths within the human eye, aiming to elucidate the impact of wavelength on the optical properties of these tissues.

The absorption properties of ocular tissues are dependent on wavelength, influencing the distribution and propagation of laser energy. Notably, the cornea demonstrates significant

absorption at shorter wavelengths, especially within the ultra-violet spectrum, thereby justifying the prevalent use of lasers with a 193 nm wavelength in refractive procedures such as photorefractive keratectomy. [6], [7].

This work introduces a novel Finite-Difference Time-Domain (FDTD) model of the human eye featuring a biconvex lens with a tailored GRIN profile (refractive index = 1.376) and anatomically validated dimensions, enabling precise analysis of wavelength-dependent energy distribution. FDTD is an advanced numerical technique for solving Maxwell's equations, to simulate the propagation of electromagnetic waves within the heterogeneous and anisotropic media of the eye. The findings are anticipated to offer significant insights into the variations in energy distribution patterns and their potential implications for the safety and efficacy of optical applications.

II. METHODOLOGY

The FDTD method was utilized to model the propagation of electromagnetic waves within the human eye. This method relies on the discretization of Maxwell's equations across both temporal and spatial domains [8], [9], facilitating a precise simulation of the interaction between electromagnetic waves and the heterogeneous tissues of the eye.

An anisometric two-dimensional model of the human eye was developed, which encompasses the cornea, aqueous humor, lens, and vitreous humor. The geometric parameters and refractive indices of these anatomical components were sourced from well-established literature, which provides a comprehensive analysis of light propagation through ocular tissues [10]. The region of the lens situated posterior to the cornea exhibits a graded refractive index (GRIN) distribution. [11], [12]. The anatomical configuration of the human eye will be presented, accompanied by the corresponding actual dimensional measurements.

This approach introduces a numerical algorithm designed for the resolution of electric and magnetic fields. The governing

equations for the electric and magnetic fields are presented through the subsequently updated expressions.

$$\begin{aligned}
H_y \Big|_{i,j+1/2}^{n+1/2} &= H_y \Big|_{i,j-1/2}^{n-1/2} - \frac{\Delta t}{\mu_0} \left(\frac{E_z \Big|_{i,j+1}^n - E_z \Big|_{i,j}^n}{\Delta} \right) \\
H_x \Big|_{i,j+1/2}^{n+1/2} &= H_x \Big|_{i,j-1/2}^{n-1/2} - \frac{\Delta t}{\mu_0} \left(\frac{E_z \Big|_{i,j+1}^n - E_z \Big|_{i,j}^n}{\Delta} \right) \\
E_z \Big|_{i,j}^{n+1} &= E_z \Big|_{i,j}^n + \\
&\frac{\Delta t}{\epsilon_0} \left(\frac{H_x \Big|_{i+1/2,j}^{n+1/2} - H_x \Big|_{i-1/2,j}^{n+1/2}}{\Delta} - \frac{H_y \Big|_{i,j+1/2}^{n+1/2} - H_y \Big|_{i,j-1/2}^{n+1/2}}{\Delta} \right)
\end{aligned} \tag{1}$$

Here, the subscript is the spatial position, and the superscript denotes the time steps. The calculations were performed by providing input parameters such as the refractive indices of the human eye, its proposed geometry, and the wavelength of the light source.

The light source used was a short pulse of light can be expressed as a sinusoidal wave as follows: $E_{src} = E_0 e^{-(y-y_0)^2/\sigma^2} \sin(2\pi ft)$. The source is a sinusoidal-modulated plane wave spanning 380–750 nm, propagating along the optical axis (z-direction). The wavelength range of the source is 380 to 750 nm. The refractive indices employed for the construction of the geometry, which are 1.336 and 1.337, serve as determinants of the steepness or smoothness of the GRIN profile. The simulations were executed utilizing a custom-developed FDTD code, which has been validated against analytical Mie scattering solutions for spherical geometries in a sagittal plane.

Figure 1a shows the cross section of the plane x-z perpendicular to the direction of propagation z of the geometric structure of the human eye, where the different interference regions of the electromagnetic field $\mathbf{E}$ are highlighted in the focal point at 450 nm. These regions are essential for comprehending the propagation of light through the eye and the manner in which different modes interfere at the focal point.

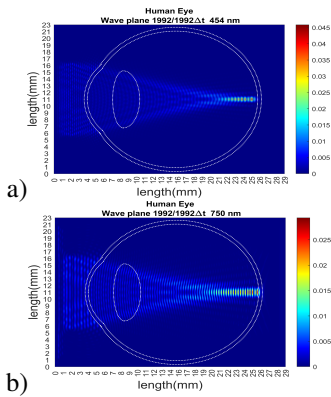


Fig. 1. A single snapshot of the E_z in the plane $x-y$ distribution at a) 450 nm and b) 750 nm, in the time-domain ascertained through the application of the two-dimensional FDTD, highlighting interference effects influenced by the lens GRIN profile and tissue anisotropy.

Figure 1b illustrates the energy distribution along the optical axis of the human eye for a short pulse with a wavelength

of 750 nm. Energy concentration becomes more pronounced in the posterior regions of the eye, approximately between 23–26 mm, signifying the focal point of the optical system. The peak energy intensity in these regions surpasses that observed closer to the cornea, demonstrating that the lens of the eye efficiently focuses the 750 nm wavelength in the posterior segment, plausibly within the vitreous humor.

III. CONCLUSIONS

Both wavelengths focus energy within a similar region of the posterior segment of the eye (23–26 mm), which corresponds to the retinal area. Nevertheless, the 750 nm pulse demonstrates a more restricted focal region, whereas the 450 nm wavelength exhibits a slightly greater spread due to dispersion and scattering phenomena. The 450 nm wavelength appears particularly appropriate for superficial diagnostic methodologies where the enhanced resolution offered by shorter wavelengths is desirable. Conversely, the 750 nm wavelength proves more beneficial for applications necessitating deeper tissue penetration and precise energy focusing, such as retina-targeted laser therapies or imaging modalities. Subsequent research will broaden this framework to encompass the examination of pathological ocular conditions, such as cataracts or myopia, with the objective of quantifying chromatic aberrations and variations in focal length.

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