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Optical-effect Analysis of Nanoscale Collagen Fibers

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To understand the cause of the high light transmittance of the human eye, the optical effects of the collagen fibers of the stroma layer, which constitute the majority of the cornea, were analyzed. These collagen fibers, approximately 20 nm in diameter, have a regular arrangement. Accordingly, the optical properties of the collagen fibers and the fiber layer were analyzed by simulation. A standing wave was formed in the incident space by the overlapping incident light and the light reflected by the plate. In addition, it was confirmed that when the collagen fibers are arranged in a layer, the light transmittance periodically changes, depending on the number of fiber layers. The standing wave was formed in the incident space, and the light's intensity distribution was changed by the nanoscale collagen fibers in the section with the collagen layer, which affected the transmittance. To explain this phenomenon, the collagen fiber was defined as a second light source, and an attempt was made to describe the simulation results in terms of overlap of the incident light with the light emitted from the collagen fiber.

Keywords : Collagen fiber, Fiber layer, Light transmittance, Nano-structure
OCIS codes : (330.7326) Visual optics, modeling; (330.4595) Optical effects on vision

I. INTRODUCTION

The human eye requires high light transmittance to clearly recognize information about an object using light. The cornea plays an important role in the refraction of light, and is in the form of a concave meniscus lens. The cornea consists of five layers: the corneal epithelium, Bowman's layer, corneal stroma, Desme's membrane, and corneal endothelium. The stroma occupies about 90% of the cornea's thickness, with collagen fibers about 20 to 30 nm in diameter gathering to form a fibrous layer. Unlike other collagenous tissues of the human cornea, the corneal stroma is transparent, with adjacent collagen layers arranged in a 90° lattice [1, 2]. The structural properties of the stroma have a great effect on overall corneal transparency [3-6]. Therefore, analyzing the optical phenomena that occur as light passes through the collagen-fiber layer is very important for understanding the optical effects of the eye.

The intensity of light, which changes as incident light passes through a specific medium, is evaluated in various ways. For nano-materials such as collagen fibers, transparency is typically measured by the degree of scattering of light rays that occurs after transmission. As the incident light proceeds, part of scattering of light rays that occurs after transmission by interaction with the medium nonetheless proceeds in the same initial direction, without phase change [7].

The energy intensity of the scattered light is closely related to the density of atoms or molecules constituting the medium, the change of direction due to interaction, and polarization. Therefore, to evaluate the degree of scattering of incident light, it is appropriate to use a modeling method capable of comparatively analyzing the results studied under various conditions.

The three-dimensional nanostructure simulator OptiFDTD (Optiwave Systems Inc., Canada) was used to analyze the optical properties of collagen fibers. Simulation space was set to 4.0 μm, 4.0 μm, and 4.5 μm along the *x*, *y*, and *z* axes respectively. The incident light was *x*-axis polarized, as a Gaussian beam with a center wavelength of 589 nm

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and a range of 300~900 nm. At the boundary of the simulation space, the UPML (Unsplit Perfectly Matched Layer) method was used, to absorb the electromagnetic waves and minimize reflection.

II. MATERIALS AND METHODS

2.1. Collagen Plate

To compare and analyze the optical phenomena during light's passage through the cornea, we first analyzed the optical characteristics of a collagen plate 22.5 nm thick, *i.e.* the diameter of a collagen fibers.

Figure 1 shows the electric field distribution in the simulated region when a Gaussian distribution of light is incident upon a plate 22.5 nm thick with a refractive index of 1.55. The thickness of 22.5 nm is used because a previous study investigated the highest light transmittance at 20~30 nm diameter of collagen fibers [7]. Figures 1(a), 1(b), and 1(c) respectively show the electric field intensity distributions on the plane including the optical axis in the beam propagation direction, and on the vertical and horizontal lines. The result of Fig. 1(b) is that the incident light is a Gaussian beam, and the standing wave in (c) is formed by the superposition of the incident light and the light reflected by the plate. The center wavelength of the incident beam is 589 nm, and the period of the standing wave shown in Fig. 1(c) is approximately 300 nm. The light transmittance for the center wavelength of 589 nm is approximately 95%.

Figure 2 shows the ratio of light intensity to that of the incident light, measured by detectors placed before and after the collagen plate. The wavelength range of light included in the calculation is 300~900 nm, and the incident light beam is Gaussian centered on 589 nm. The solid black and red lines are light intensity distributions measured before and after passing through the collagen plate respectively.

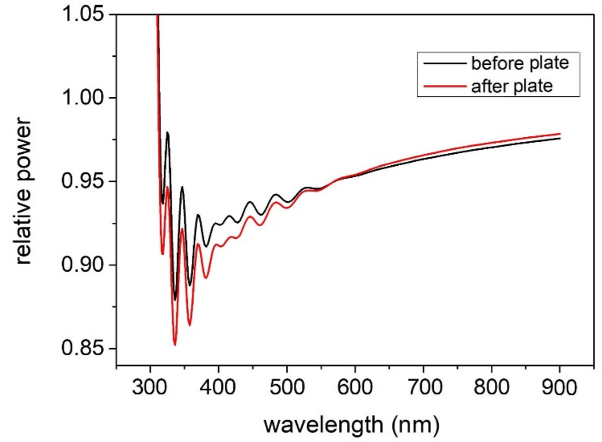


FIG. 2. Relative power versus wavelength.

The light intensity distribution shown in Fig. 2 oscillates from 300 nm to 400 nm; as the wavelength increases, the oscillation gradually weakens and disappears above approximately 600 nm. That is, in the short-wavelength region the relative transmittance periodically changes with wavelength, but in the long-wavelength region this periodic change disappears. Another feature is that the red and black traces cross at approximately 600 nm wavelength. In other words, as the plate is passed the intensity decreases at short wavelengths, but increases slightly at long wavelengths.

2.2. Collagen Fibers and Collagen-fiber Layer

To analyze the optical action of collagen fibers, we investigated the light intensity distribution and transmittance by injecting a Gaussian beam centered on 589 nm into collagen fibers and fiber layers. Figure 3 shows a compa-

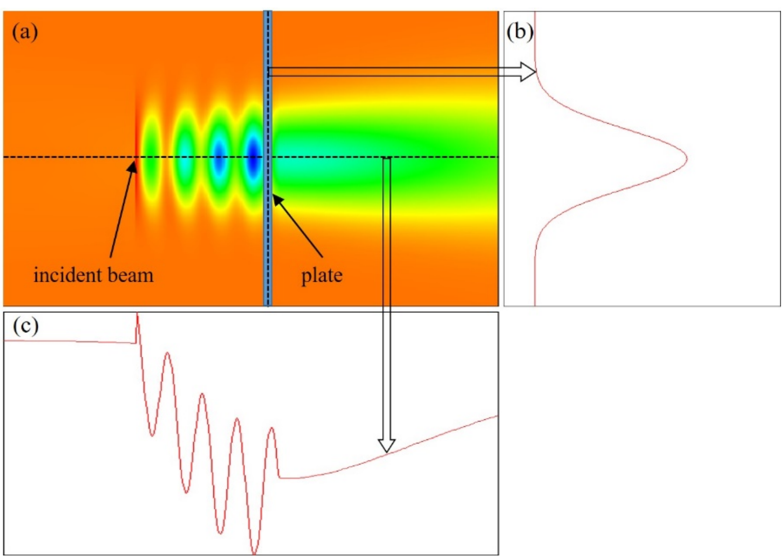


FIG. 1. Electric field distribution: (a) simulation area, (b) along a vertical line, (c) along the central horizontal line.

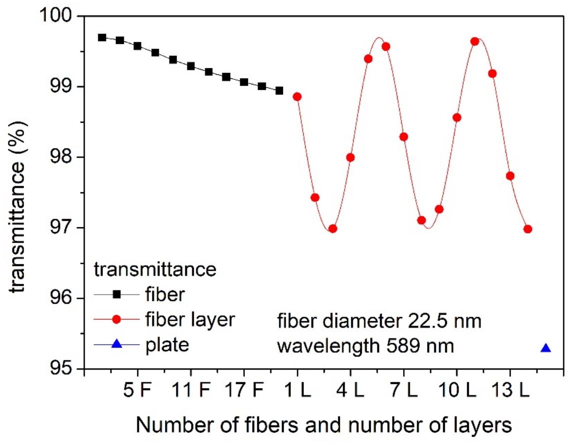


FIG. 3. Light transmittance for collagen fibers, fiber layers, and plate.

rative analysis of light transmittances for collagen fibers, fiber layers, and a fiber plate, for the center wavelength of 589 nm.

The left part of the graph (black solid squares) is the light transmittance for collagen fibers erected perpendicular to the light's propagation direction. Both the diameter of each fiber and the spacing between fibers are 22.5 nm. It can be seen that the transmittance decreases with increasing number of collagen fibers.

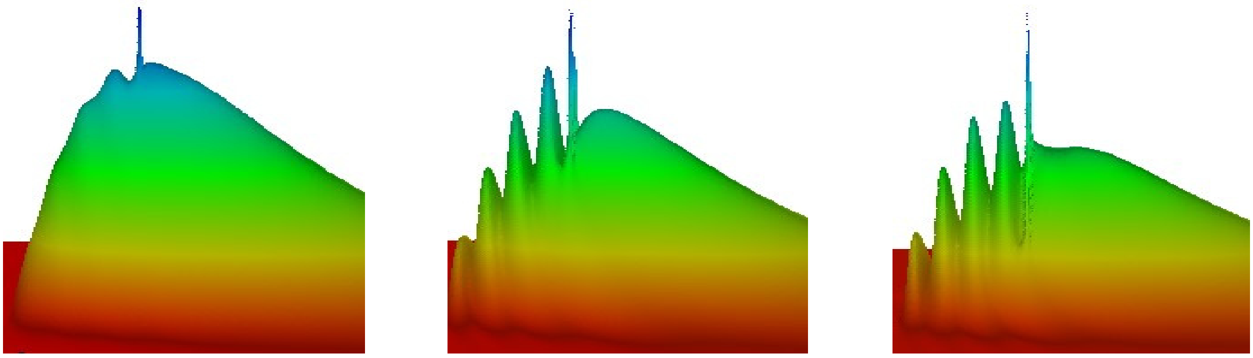
The middle part of the graph (red solid dots) is the light transmittance analyzed by layering collagen fibers at regular intervals. Again, the diameter, inter-fiber spacing, and inter-layer spacing were set at 22.5 nm. It can be seen that the transmittance periodically changes as the number of layers increases, and the transmittance value is repeated every three layers, such as at layers 4 L, 7 L, and 10 L. The causes of the periodic change are analyzed in the next section.

The lower right (blue solid triangle) is the light transmittance for the 22.5 nm thick collagen plate mentioned in the previous section, which shows that the transmittance through this plate is lower than that through fibers or layers of fibers.

2.3. Optical Properties of Collagen Fibers and Fiber Layers

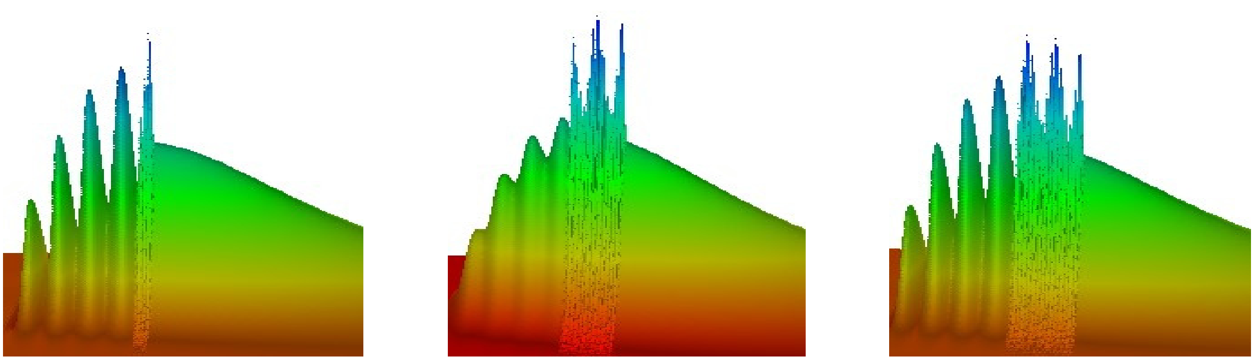
In the previous section, the transmittance of collagen fibers, fiber layers, and a fiber plate were investigated. In this section, we examine the field-strength distribution to analyze the cause of those results.

Figure 4 shows the distribution of the electric field oscillating in the direction of the incident beam, for collagen fibers with a diameter of 22.5 nm aligned perpendicular to



(a) (b) (c)

FIG. 4. Electric field distribution for various numbers of collagen fibers: (a) 1, (b) 11, (c) 21.



(a) (b) (c)

FIG. 5. Electric field distribution for various numbers of collagen-fiber layers: (a) 3, (b) 11, (c) 14.

the direction of the incident beam. In the case of a single fiber, a change was observed only at the position where the fiber was placed, as shown in Fig. 4(a). On the other hand, as the number of fibers increases, the standing-wave characteristics become stronger, Fig. 4(c).

Figure 5 shows the electric field distribution along the optical axis, for fiber layers aligned side by side in the vertical direction of the light propagation direction. In a fiber layer, standing waves are formed in front of the fiber layer, as in the plate. As light passes through the fiber layer, small-amplitude vibrations occur, and after passing through the layer the intensity gradually decreases. The reduction in field strength behind the collagen layer can be seen as a natural decrease, since light was absorbed from the sides of the simulation domain after passing through the collagen layer.

What is unusual is that the electric field distribution changes periodically as the number of fiber layers increases. In Fig. 5 the standing-wave phenomenon in front of the collagen layer changes periodically. In other words, the standing-wave characteristics are weakened in Fig. 5(b), and then stronger again in Fig. 5(c).

In the previous section, it was confirmed that the value of the change in light transmittance was repeated in three-layer cycles. From this can be seen a correlation between the change in the standing-wave characteristic and the light transmittance: When the transmittance is high, the standing-wave characteristic is weakened.

2.4. Light Transmittance for a Collagen-fiber Layer

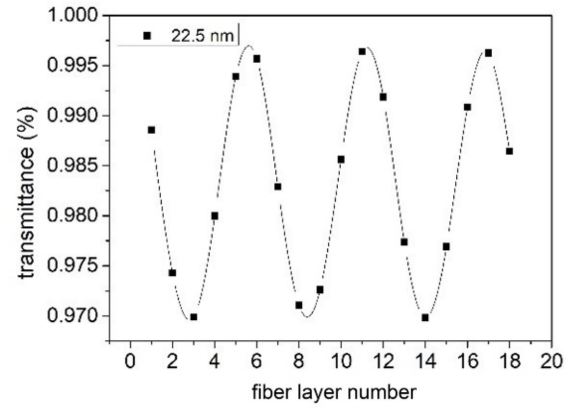
In the previous section, when the diameter of the collagen fibers constituting the layer was 22.5 nm, it was confirmed that the light transmittance periodically changed according to the number of layers. To determine how the periodic phenomenon of light transmittance is affected by the diameter of each collagen fiber, the results for diameters of 22.5, 45.0, and 60.0 nm were analyzed.

Figure 6 shows the transmittance at 589 nm for the collagen-fiber layer. It can be seen that the transmittance changes periodically in every case, while the detailed characteristics vary slightly depending on the diameter of the constituent fibers.

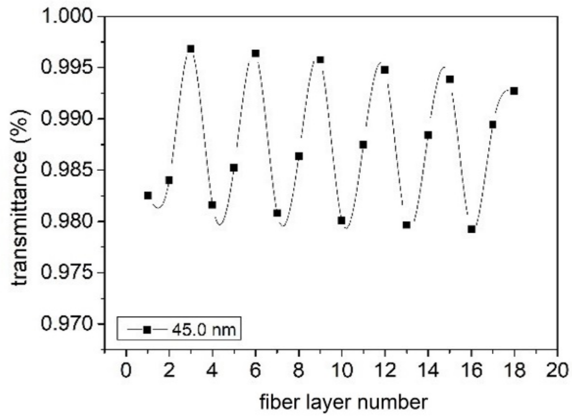
The maximum light transmittance does not decrease from left to right when the diameter is 22.5 nm, while it gradually decreases when the diameter is 45 nm. The transmittance for a diameter of 60 nm shows a change like a beat wave. The ratio of vibrational periods in graphs (a), (b), and (c) are approximately 3:6:8, which corresponds to the diameter ratio 22.5:45.0:60.0. An analysis of this ratio follows in the next chapter.

III. THEORETICAL ANALYSIS

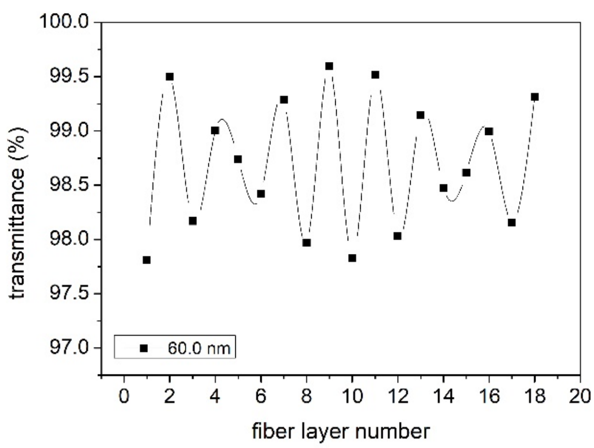
When incident light passes through a collagen-fiber space, a change in electric field distribution occurs inside the collagen fiber, as shown in Figs. 4 and 5. Based on this, we visualize the collagen as a new light source, and explain the results in Fig. 6. For this purpose, the light intensity distribution and transmittance in space were analyzed by the superposition of incident light and the light emitted (reflected or scattered) from collagen fibers.



(a)



(b)



(c)

FIG. 6. Light transmittance according to number of collagen-fiber layers for fiber diameters of (a) 22.5 nm, (b) 45.0 nm, and (c) 60.0 nm.

3.1. Superposition Model

We attempted to theoretically analyze the optical properties of superimposed light. Figure 7(a) shows the electric field distribution by simulation, and Fig. 7(b) is a conceptual diagram of the superposition model introduced to analyze the results. The intensity (amplification or cancellation) of light by superposition is determined by the phase difference of the superposed light beams. The superposition model in this study investigated the change of light intensity according to the phase difference caused by the path difference between the original light source and the new light sources.

The path difference is caused by two things: the distance L between the light source and the first collagen layer, and the spacing $2d$ between collagen structures, where d is the fiber diameter. As a result, the phase difference generated by the n^{th} collagen layer is

$$\phi^{(n)} = \frac{2\pi}{\lambda}(L+(n-1)2d). \tag{1}$$

It is well known that the wave number and angular frequency are $k=2\pi/\lambda$ and $\omega=ck$ respectively. Using these two parameters, the wave function of the incident light can be written as

$$y^{(0)} = \sin(kx-\omega t), \tag{2}$$

and that of light emitted by collagen in the n^{th} layer can be written as

$$y^{(n)} = a^{(n)}\sin(kx \mp \omega t-\phi^{(n)}). \tag{3}$$

Here, the symbol in the phase term indicates the direction of light travel, with - and + indicating the forward and backward directions respectively. The coefficient $a^{(n)}$ in Eq. (3) is introduced as an attenuation constant, to reflect the weakening of the light intensity generated by the collagen fibers. In the incident region from the light source to the first fiber layer, the light reflected from the first collagen layer and the incident light overlap to form a standing wave, as seen in Fig. 4(c).

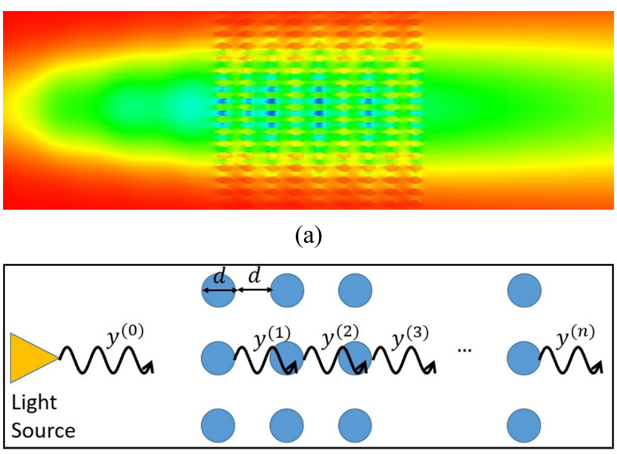
In this study, to understand the cause behind the simulation results, the intensity of the superposition of incident light and light generated by each layer was analyzed. The intensity of the superposed light is

$$power^{(n)} = \left|\Sigma_{i=0}^{n} y^{(i)}\right|^2, \tag{4}$$

where $y^{(0)}$ and $y^{(n)}$ represent the intensity of incident light and that generated by the n^{th} collagen unit respectively.

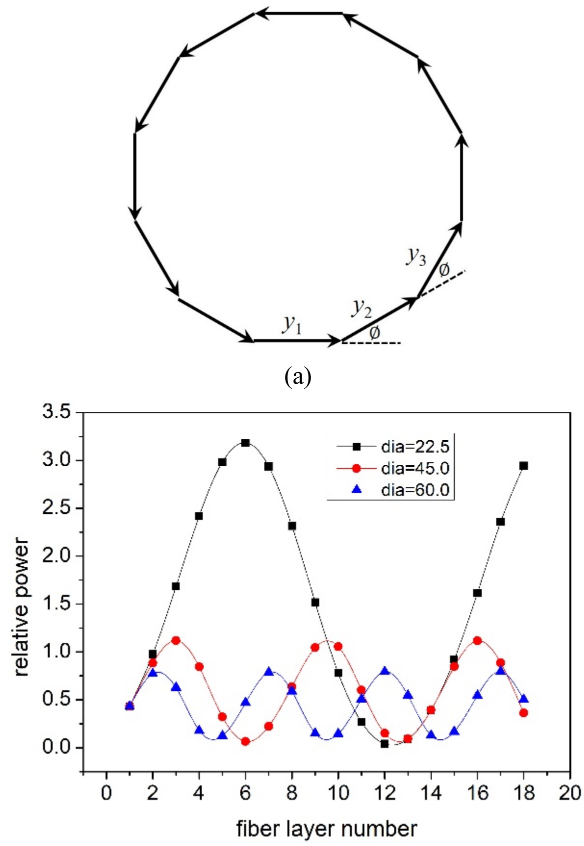
3.2. Attenuation Effect

Figure 6 shows the results of light transmission simulated for collagen-fiber diameters of 22.5, 45.0 and 60.0 nm, depending on the number of collagen layers. All three cases have a common feature of periodic change, while each has its own characteristics. For 22.5 nm the output changes periodically, but the intensity remains unchanged. On the other hand, for 45.0 nm the maximum intensity gradually decreases with periodic change. For the final value of



(a) (b)

FIG. 7. (a) Electric field distribution, and (b) conceptual drawing of the new-light-source model.

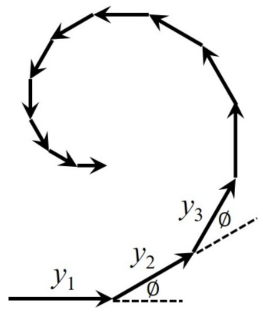


(a) (b)

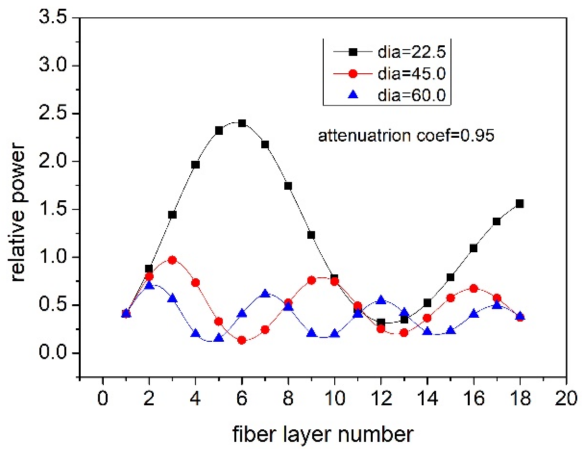
FIG. 8. For $a = 1$, (a) phase analysis of field superposition, and (b) numerical analysis.

60.0 nm, the overall intensity changes at long intervals, with periodic changes as in a beat phenomenon. To illustrate each situation in Fig. 6, we analyzed the effect of the attenuation factor.

Figures 8(a) and 8(b) respectively show the superposition plot of the electric field by the phasor method, and the numerical calculations for the case of $a = 1$. As the number of collagen layers increases, the superposition intensity only changes periodically and persists without decreasing. This is similar to the result of Fig. 6(a), showing the output of collagen with diameter 22.5 nm.



(a)



(b)

FIG. 9. For $a < 1$, (a) phase analysis of field superposition, and (b) numerical analysis.

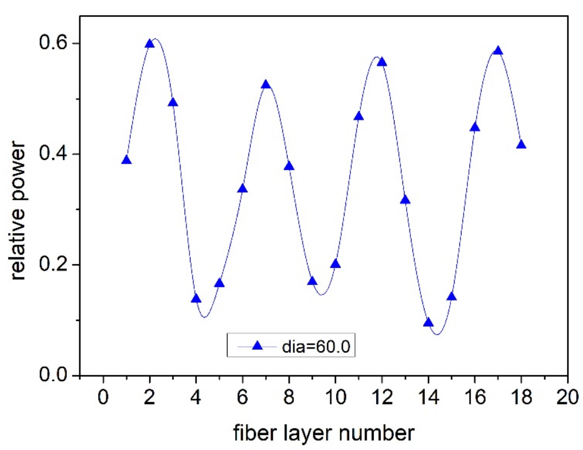


FIG. 10. Numerical results for cases with changing attenuation coefficient.

Figures 9(a) and 9(b) are respectively a superposition plot of the electric field for the phasor method, and numerical calculations for $a < 1$. As the number of collagen layers increases, not only does the overlap intensity change periodically, but also the strength gradually decreases. This is similar to the result in Fig. 6(b), which shows the output of fibers 45 nm in diameter.

Finally, for the case where the attenuation factor changes periodically, *i.e.*:

$$a^{(n)} = \alpha^x \beta^y \gamma^z (\alpha, \beta, \gamma < 1,\ x+y+z = n). \quad (5)$$

The result of numerical analysis is shown in Fig. 10. This result is similar to that of Fig. 6(c), where the collagen-fiber diameter is 60.0 nm. If the attenuation coefficient is calculated precisely by introducing more various values, the result becomes closer to that in Fig. 6(c).

IV. DISCUSSION AND CONCLUSION

We analyzed the optical effects of the collagen fibers that make up the cornea of the human eye. Furthermore, to analyze the root cause of the very high light transmittance of the cornea, we compared and analyzed simulation results according to the number of collagen fibers, the number of fiber layers, and the fiber diameter. To understand the simulation results, an electric field superposition model is introduced.

According to the simulation results, when a collagen plate is installed, standing waves are formed by superposition of incident and reflected light in the space before the plate. As the number of collagen fibers increases, the standing-wave phenomenon gradually strengthens and the transmittance decreases slightly.

As the number of collagen layers increases, the transmittance periodically changes. This phenomenon is different depending on the diameter of each collagen fiber. At a diameter of 22.5 nm, the transmittance changes periodically as the number of layers increases but the intensity does not decrease, though for the case of 45 nm the intensity gradually decreases while periodically changing. For 60 nm diameter, the variation is similar to the phenomenon of beats, weakening and strengthening with periodic change.

To account for the differences in output according to diameter, a superposition model of light was introduced. The collagen fiber was considered a new light source, and the intensity distribution due to the superposition of the incident light and the light emitted from each collagen unit was analyzed. Results for diameters of 22.5, 45, and 60 nm were analyzed with varying attenuation factors, to represent the intensity of light emitted from the new light source in the superposition.

The 22.5 nm results were in agreement with model results with all attenuation factors having the same value, and the 45 nm results were consistent with the results for the decay factor decreasing at a constant rate. Finally, it was confirmed that the result for 60 nm corresponds to a combination of several different attenuation factors.

As a result, in the previous study, the highest light transmittance was for a collagen fiber 22.5 nm in diameter [7]. According to the results, it was confirmed that even if the number of collagen layers increases at 22.5 nm in diameter, the light transmittance periodically changes but the intensity is maintained without weakening. The reflection and scattering phenomena due to the change of collagen-fiber diameter and spacing combine to maintain high light transmittance at a diameter of 22.5 nm.

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