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# A Study on the Focusing Properties of a Diffuse Plano-curved Lens

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The focusing properties of a plano-convex and a plano-concave lens made of diffuse scattering media were investigated by using numerical simulations. Whole human blood was chosen as the medium for convenience as it is a well-defined scattering media with an average concentration of scattering particles. A million parallel rays at a wavelength of $525 \times 10^{-9}$ m were launched parallel to the optical axis toward the planar side of the lens. Rays emerge on the curved side after having undergone numerous scatterings with blood constituents. The number of rays reaching the predefined receiver plane was counted and was assumed to be related to the total optical power. The result indicated that the collecting efficiency, defined as the ration of the collected to the launched power, improved monotonically toward the concave lens. A closer examination on this seemingly abnormal behavior produced evidence that strongly suggests that this should be due to the difference in their effective thickness, not the general shape or the curvature of the lens geometry.

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## I. Introduction

Light travels through various media in the course of propagation. The propagation through a well-defined homogenous medium like optical glasses are well understood and is fully exploited in numerous applications; imaging optics is an obvious example. The fundamental boundary value problem that dictates how electric and magnetic fields behave upon crossing the boundary between two media, and is succinctly formulated as Snell's law [1]. This is the law that is utilized in all fields of optical applications when light is modeled as a collection of "rays". This law and the consequent propagation of rays are reliable only when the boundary is well-defined and the propagation medium homogeneous. Of course one can, in principle, apply the propagation relations to inhomogeneous media, treating the media as the collection of layers of medium with each incremental layer homogeneous in that layer. This is acceptable in principle yet impractical in real systems for so many reasons.

Propagation through turbid media is another story. Light propagation through this kind of media is difficult to model [2]. This is due to the strong absorption and scattering from molecules and particles in the medium [3]. These can only be treated in a statistical manner, which implies the exact tracing of individual rays is not feasible. This does exclude the light transmission through turbid media from finding any practical applications; one of such an application can be found in biomedical optics where diffuse imaging still provides certain pertinent information about the constituents the light encountered in the course of traversing the medium. Diffuse optical imaging is an example of such an application. Jang *et al.* [4] studied the feasibility of utilizing light scattering to estimate the concentration of human white blood cells.

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Recently we noticed the potential ambiguity on the focusing properties of the optical lens with turbid medium filling the space between two optical surfaces constituting the lens. Focusing properties are well described by Snell's law for transparent medium should the refractive index of the medium be known to a reasonable accuracy. If the medium should contain scattering and diffusing elements throughout, the output pattern for an input beam of rays will not follow the expectation from the Snell's law of refraction. It is our goal in this study to examine the consequence of filling the space between lens surfaces with turbid medium. The outcome could be utilized in understanding the focusing properties of the cataract eye, deformable liquid lenses and optical systems dealing with human body fluids which almost all the times contain certain amount of scattering and absorbing elements.

## II. Lenses with turbid media

The lens under consideration was modeled with the LightTools$^{TM}$ [5] package. This package allows the user to designate the medium and the system resorts to Monte Carlo methodology to trace the path of every ray that was launched from the predefined light source. The direction of the launched light of course can also be adjusted to reflect the actual radiation pattern.

For this study, we modeled a plane-curved lens, where the radius of the curved surface was allowed to vary. The real lens should include thin transparent films or layers on both sides of the lens. Since the software model allows the user to define the lens geometry with no physical restrictions, we defined a model with the diffusing medium only, without conventional sheath layers on both ends. The medium chosen for this purpose was human whole blood. Out of many potential candidates, whole blood was chosen for its universality; scattering properties, absorptivity and concentration of its constituents, albeit relatively minor variations between individuals.

We set up a model of a plano-curved lens made of the aforementioned medium. The diameter of lens was $5 \times 10^{-3}$ m, with the edge thickness of $1 \times 10^{-3}$ m. The curved side was modeled as a spherical surface whole sag was between $-0.5 - +0.5 \times 10^{-3}$ m. These approximately correspond to the radii of curvature of $-6.25 - +6.25 \times 10^{-3}$ m.

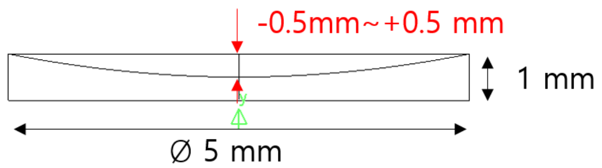


Fig. 1. (Color online) The lens model. The space between two surfaces are filled with human whole blood. The deflection (concave in this case) could be either positive or negative.

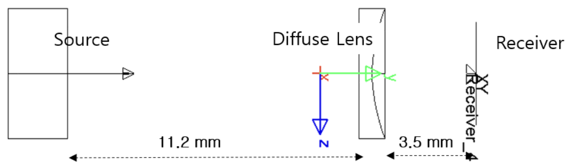


Fig. 2. (Color online) System layout.

The system configuration requires the user to define the light source and the direction of the emanating rays. For simplicity in comparing different lens configurations, we assumed circular source, with rays launching from the surface at normal angles. The diameter of this source was $5 \times 10^{-3}$ m and the source as positioned $11.2 \times 10^{-3}$ m off the planar side of the lens. This distance makes no difference since we only take parallel rays coming on to the planar surface at right angles. The receiver plane, required in the process of building the model, was positioned $3.5 \times 10^{-3}$ m from the curved surface. The distance to the receiver was chosen based on preliminary runs: too far a distance resulted in too few rays reaching the receiver. The receiver was assigned the square dimension of $4 \times 10^{-3}$ m $\times 4 \times 10^{-3}$ m, considering available sizes of a photo sensor.

With the optical models set up as described above, the performance of the system was tested with the lens medium replaced with pure water. Since the maximum radius of curvature of the convex surface was found to be 6.25 mm, the focal length of the water filled lens is found with the Lens Maker's Formula. [6] to be

$$\frac{1}{f} = (1.333 - 1)\left(\frac{1}{\infty} + \frac{1}{6.25}\right) \tag{1}$$

$$f = 18.8 \times 10^{-3}\mathrm{m} \tag{2}$$

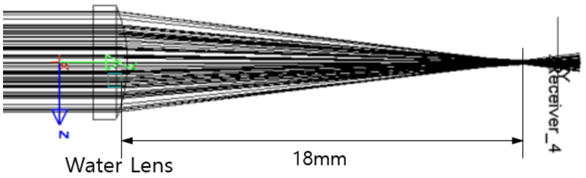


Fig. 3. (Color online) Verifying the fidelity of the lens model of Fig. 1. The medium was replaced with water and parallel rays come to a focus as expected. The focal distance is shown from the rear principal plane.

The convergence of rays from a convex lens is the testimonial that the system is properly set up. The paraxial focal point as predicted by Eq. 1 should be buried in the figure 3 by non-paraxial rays converging on the "best focus" and be located a bit further right of the best focal point.

## III. Beam Focusing Properties of Lenses with Diffuse Medium

The properties of the diffusing medium, human whole blood, were adopted as provided in the software package. A total of $10^6$ non-sequential parallel rays with $525\times10^{-9}$ m wavelength were launched parallel to the optic axis onto the test lens with varying radius of curvature. A total of 1.0 watt optical power was assigned to launched rays and the power landing on the receiver was tallied for each lens shape. Figure 4 is an illustration of scattered rays for lenses with maximal bending, $\pm5\times10^{-3}$ m at the center. Lens icons are added on each for graphical clarity. Rays that failed to reach the receiver were abandoned from further tracing. Only those rays that found their way to the receiver are traced and shown. One can clearly observe, upon visual inspection, that more rays reached the designated receiver plane with the concave lens geometry. This goes against the common notion that the parallel light through a clear convex lens converges on or around a focus.

With such a precursory observation, we ran simulations on the lens model with $10^6$ parallel rays launched from the light source. Optical elements were arranged as shown in Fig. 2. The total optical power of 1.0 Watt was emitted parallel to the optical axis and the power reaching the receiver plane of $4\times10^{-3}$m $\times$ $4\times10^{-3}$ m area was computed. Figure 5 shows the light collection

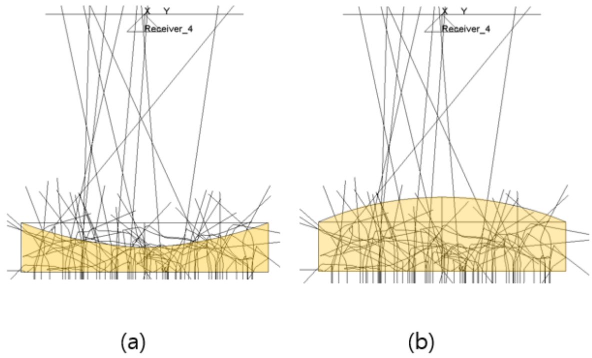


Fig. 4. (Color online) Ray tracing diagrams, illustrating the relative efficiency of power concentration. The concave arrangement of (b) produced higher concentration of optical power. More lights reach the receiver plane (vertical line on the right) with the concave lens (b).

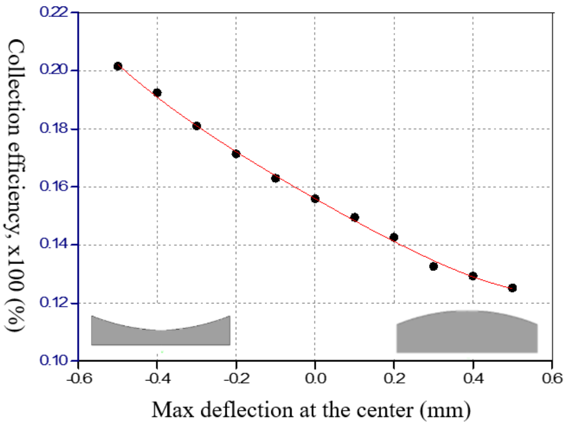


Fig. 5. (Color online) Relative collection efficiencies of differing lens configuration. Lights were incident onto the flat side of the lens at normal angles.

efficiency, defined as the ratio of collected power on the receiver to the incident power on the front surface of the lens, versus various lens shapes. The lens shape is denoted by the maximum deflection of the curved surface measured at the center. The max deflection of 0.4, for example, indicates a plano-convex lens whose curved vertex is located $0.4\times10^{-3}$ m above the plane defining the exit side of the lens.

One would note that the conventional focusing behavior of the optical lens with clear media is not present with turbid lenses; rather one finds the opposite behavior that the concave lens produces concentration of the transmitted light.

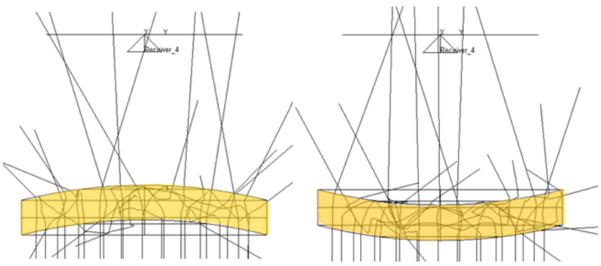

Fig. 6. (Color online) Sample light paths through lenses with identical thickness, oriented in both directions. The efficiency in both cases are 24.1% (left) and 24.6% (right), which should be within the statistical variance.

## IV. Effect of the lens shape and the thickness

Simulation data so far tend to indicate that the behavior of the lens filled with turbid media behaves against the commonly accepted view that the convex lens focuses the parallel incoming light. The nature of this abnormal behavior remained unexplained, and it was suggested that the lens shape is rather irrelevant, but the thickness is not. Review of Fig. 5 could lead one to conjecture that the concave turbid lens is less efficient in bringing light together compared to the convex one. Reviewing Fig.5 from another perspective, one could find that the convex lens is effectively thicker than the concave for the same absolute radii of curvature. Since the medium used for the simulation is strongly absorbing and scattering, the difference in the effective thickness should definitely influence the light throughput in the forward direction. In order to study the effect of the lens shape, we designed a concave-convex lens shape with identical radii of curvature on both sides but with opposite sign as shown in Fig.6. Since these two were of the same thickness, any difference in light throughput should be attributable to the lens shape.

With this model, the newly computed result showed efficiencies of 12.44% and 12.54% respectively. As such, one can conclude without any doubt that, for the lens shape filled with strong lossy medium, the effect of refraction at the bounding surface is negligible compared to the one from random scattering. Those “lenses” used in Fig. 6 do not have the functionality of the lens in strict sense since two bounding boundary surfaces have identical radii of curvature and the light gathering efficiencies at the receiver plane are practically indistinguishable. This result should provide an evidence that the shape of the bounding surface would not play a significant role in the focusing behavior of these specific lenses filled with lossy and scattering media.

## V. Concluding Remarks

Diffuse scattering is the one topic where the exact prediction of ray propagation is not realistic. One can only rely on statistical predictions based on collective treatment of all relevant parameters involved in the scattering. We set out to investigate the effect of lenses made of one of such a turbid media, human whole blood via numerical simulations. The preliminary data displayed an obvious trait that the concave lens was more efficient on collecting parallel light. This rather unexpected behavior was at fist considered an artifact of strong forward Mie scattering. Even though careful attention was paid in the lens model to ensure relevant parameters were kept identical, the thickness could not; two lenses could not be made of identical thickness for obvious reasons. To clarify this ambiguity between the lens shape and the thickness, two lens models were tested, made of equal thickness and identical absolute radii of curvature only facing the opposite direction with respect to the incoming light. This resulted in irrefutable conclusion that it was the “effective” thickness that dictates the light collection efficiency, not the lens geometry, that determines the outcome with lens made with strongly scattering and absorbing media.

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