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A Swimming Goggles Optical Design by Fresnel Lenses †

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Abstract: Currently, many swimming goggle lenses use optical plates to maintain zero refractive power in air and water. However, people's widespread use of 3C products has increased myopia significantly, so lenses have a demand for refractive power. Lenses will have different refractive power problems in water and air media. Therefore, we solved the refractive power change in air and water by using a plane Fresnel lens with a diopter to replace plano-concave lenses. In this study, a first-order design was created and then the microstructure of the Fresnel lens was optimized using optical software. The Fresnel lens simulation results showed that the error was within 5%, which was compared with the data using the lensmaker's equation calculation. For swimming goggles, this error value is tolerable for human vision.

Keywords: Fresnel lens; refractive power; refractive index

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1. Introduction

In summer, many people go to the beach or swimming pools to cool off, and most swimmers wear swimming goggles to improve their visibility and protect their eyes from harmful chemicals. Thus, the choice of swimming goggles is crucial [1,2]. Swimming goggles separate the eyes from the water and restore air contact in the swimming goggles, which helps people to see objects in the water better than they would without goggles. The most common swimming goggles have a spherical surface, because the surface of the lens is slightly convex for the refractive power in the water. These lenses have a similar effect to a concave lens. Without myopia, it is similar to wearing myopia glasses. When swimming, eyes come to have a high degree of astigmatism in a normal field of vision due to repeated entry into the water over a short period; this causes eye damage and fatigue, with dizziness, vomiting, and other symptoms in the body. A proper pair of swimming goggles must maintain consistent vision in and out of the water without causing dizziness and with the functions of being waterproof, anti-fog, low resistance, causing no pressure on the eyeballs, a wide field of vision, and a high light transmittance. Swimming goggles with vision correction must have the same function as general land myopia glasses in water [3,4]. They have a refractive error correction function, accurately fusing left and right eye images and maintaining the same pupillary distance. The lens must be light, so that the field of vision is not distorted. Swimming goggles adopt an afocal lens, which solves the diopter's problems of spherical and curved swimming goggles. People with myopia and astigmatism must carefully choose goggle lenses with a suitable refractive power of the lens.

In this study, we designed the refractive power of a swimming goggles lens with Fresnel lenses, which are widely used in various optical applications and whose most significant advantages are their lightweight and flat optical surfaces. Basic design rules were applied in the first-order design and feasibility studies. Fresnel lenses work on the principle that the refractive index of the lens is contained only on the surface of the lens, removing as much optical material as possible while maintaining the curvature of the surface. Practical methods for compressing the refractive power of the lens surface to a flat surface require concentric grooves with a small prism pitch, oblique component, and draft component. The general method is to specify a tilt angle relative to the lens plane and a draft angle close to the normal. By using the Plano-Fresnel lens with a diopter to replace the plano-concave lens of swimming goggles, the different refractive power in the air and water due to different media can be overcome. By using the optimization design of the Fresnel lens microstructure, lenses with vision correction have the same refractive power in two various media.

2. Principle of Fresnel Lens

A Fresnel lens, also known as a threaded lens, is designed with a large aperture and characterized by a short focal length, less material consumption, and a smaller weight and volume than ordinary lenses [5,6]. Figure 1 shows that (A) is a convex lens and (B) is a Fresnel lens with the same optical characteristics. When a Fresnel lens is used in afocal optical components, attention must be paid to minimizing the micro-grooves' impact on vision. In the design, this is first realized by selecting the facet spacing to be less than or equal to the resolution of the human eye, which makes the human eye almost unable to see the existence of micro prisms. A healthy human eye has a visual acuity of around one arc-minute (or 1/60°). This can be used to compute the maximum pitch size that will be visible for a given distance from the eye.

$$w \le z \times 2.91 \times 10^{-4} \quad (1)$$

where w is the maximum pitch size that can be visually resolved and z is the effective distance of the lens to the eye. To ensure that the pitch of the Fresnel lens does not produce a beat frequency limited by the minimum resolvable pitch of any other micro-prismatic components of the system, the rule to select the pitch is defined as:

$$d_1 = (m + 0.35) \times d_2 \quad (2)$$

where d_1 is the prism pitch of the Fresnel lens, m is an integer, where the larger it is the better, and d_2 is the pitch of the other micro-prismatic component in the lens. Geometrically, the smaller the prism size, the closer the small flat prism slope facets come to approximating the idealized aspherical surface. However, diffractive effects operate contrarily.

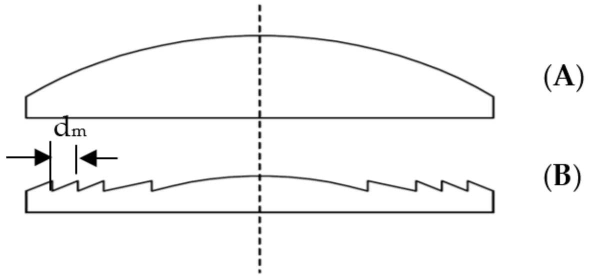

Figure 1. From a convex lens (**A**), to a Fresnel lens (**B**).

The object is beamed onto the image plane after passing through the Fresnel lens and is classified according to the relative position of the output beam and the groove on its optical surface. The Fresnel lenses are organized into a converging lens, collimator, and diverging lens. For example, the Fresnel lens with a positive focal length is used to converge light. Thus, it is used as a converging lens and collimating lens. The Fresnel lens with a negative focal length is used to diverge light as a diverging lens. Many researchers have proposed algorithms to simulate the parameters of the focusing Fresnel micro-prism structure and successfully and easily fabricated this element using diamond-cutting technology. The Zemax optical design software was used in this study to design a radial mode. The microstructure on the optical plane has many concentric grooves. It radiates outward from the center and the cross-sectional shape of the lens is a miniature right-angle prism. The value of the shape parameters, + Depth and -Frequency, are essential for the groove. If this parameter is positive, it corresponds to the depth of each groove in shot units. If negative, it corresponds to the frequency of the groove. Equations (3)–(5) optimize the pitch size of the grooves (w) and the lens diameter (Φ).

$$\Phi = (m \times h)/[1 + (m \times s_1)/(l - s_1)] \quad (3)$$

$$w = 1.5 \times (\lambda \times f)^{1/2} \quad (4)$$

$$w \leq p \times \tan[(1/60)^\circ] \quad (5)$$

where λ, f, s_1, m, l, and p are the wavelength of the light source, the focal length of the lens, the distance between the lens and the object, the magnification of the lens, the distance between the object and the observer, and the distance between the observer and the lens [4–6].

3. Design and Experiment Results

The design process included the subject requirement, first-order design, optimization of the plano-concave lens, transformation into a Fresnel lens, optimization of the microstructure parameter, image evaluation, and tolerance analysis. As there are many types of refractive errors, we considered myopia only, so the subject requirement was the diopter of the myopia. The first-order design discussed the relationship between the object, image, and lens's focal length. The thin lens formula decided the image position and size. If the distances from the object to the lens and from the lens to the image are S_1 and S_2, respectively, and the focal length of the thin lens is f in air, then the relationship between the three parameters is as follows.

$$(1/S_1) + (1/S_2) = (1/f) \quad (6)$$

This can also be put into another form.

$$X_1 \times X_2 = f^2 \quad (7)$$

where $X_1 = S_1 - f$ and $X_2 = S_2 - f$.

With myopia, a user requirement includes pupil distance, the refractive error (diopter) of the lens, the plano-concave lens, and the face size for making the goggles. The parameter of the first-order design includes the object distance, object high, image high, material of the lens, and other constraints. Optimizing the plano-concave lens makes the optical lens have no diopter difference in different object space mediums, water, and air. Other conditions, such as the back focal length, remain fixed, and the image quality and resolution are the same. In addition to obtaining the best spherical radius of the curvature, it is also possible to use aspheric surfaces. The purpose of transforming into a Fresnel lens is to use a flat optical plate to reduce the diopter difference between the lens in water and air, so the spherical surface of the plano-concave lens after optimization is converted into a Fresnel surface. In the above two steps, the focal length is calculated from the known refractive error and the radius of the curvature of the plano-concave lens can be further calculated using Equation (8).

$$S = (n_2 - n_1)/R \tag{8}$$

where R is the curvature radius of the spherical surface, S is the refractive error, and n_2 and n_1 are the refractive indices on both sides of the spherical surface.

When the unit of R is m, the unit of S is diopter (D). The curvature radius of the spherical surface of the plano-concave lens is 1.0 m and the refractive index of the lens material is 1.5. If it is used in air, S is 2.0 D. The Fresnel lens adopts a discontinuous surface profile composed of a hundred concentric rings, and tiny serrated prisms are arranged on these small rings to retain the rings' ability to focus the light toward the center or divergence. The parameters for controlling the tiny saw tooth (in µm) are the pitch angle, depth, and pitch. By optimizing the microstructure parameter of the Fresnel surface, the optical power of the Fresnel surface and plano-concave lens become the same, still with an error. The Fresnel surface replaces the spherical surface, which is only the initial condition unchanged. However, the error value needs to be within the acceptable range of vision to find the best microstructure parameters of the Fresnel surface here and meet the requirements and image quality. In the optimization method, the microstructure's frequency and pitch angle are changed to optimize the minimum light spot. After the above steps are completed, the image evaluation is performed for various aberrations and spot size values. The aberration has a spherical aberration, coma, astigmatism, distortion, field curvature, and chromatic aberration.

After the image evaluation is qualified, the tolerance analysis is performed, and the entire design is completed. Then, the pilot run is performed. Tolerance is the limitation of the processing accuracy in the lens production and manufacturing, so that after the finished product is completed, it meets the expected specifications at the design time. To meet the tolerance requirements, manufacturers must know what manufacturing and testing methods are used when producing these lenses to make the production process model consistent with reality. These engineering problems have corresponding theoretical models for analyses. For statistical tolerance, the variation in a set of inputs is taken to calculate the expected variation in the outputs of interest. In mechanical engineering, product designs are composed of features whose tolerance values are related to various aspects of these features. In this study, we conducted a preliminary design of a Fresnel lens for swimming goggles and did not elaborate on the image evaluation and tolerance analysis.

The design method was as follows. The non-sequential method of infinite grooves was used to simulate the Fresnel lens of a −2.0 D flat and concave lens. For the relevant conditions, the radius, thickness, material, and imaging spot diameter of the radial Fresnel lens were set as 60 mm, 1 mm, BK7, and 117 µm, respectively. The distance between the lens and the image plane was 500 mm. The refractive index of BK7 was 1.517 and the V number was 64.169. Table 1 lists the nine different refractive diopter lenses commonly used in stores and the related microstructure parameters used in the simulation process. These parameter values were optimized with the minimum light spot as the target. Figure 2 shows the Flow chart of Fresnel lens for swimming goggles design. Figure 3 shows the cross-sectional structure of the Plano-Fresnel lens for the swimming goggles using the layout of zemax optical design program. The blue lines are marginal rays of 0° field of view in object space, and the light ray is parallel to the optical axis. A Fresnel lens with a negative focal length diverges light for people with myopia.

Table 1. Optical parameters of nine different diopter lenses.

Plano-Concave Lens			Plano-Fresnel Lens			
Diopter (D)	f (mm)	R (mm)	Freq.	Pitch Angle (°)	Spot Size (μm)	BFL (mm)
−2	−500.00	258.50	−2	0.5	117	−500.69
−3	−333.33	172.33	−1	0.5	98	−332.48
−4	−250.00	129.25	−1	0.5	117	−250.8
−5	−200.00	103.40	−1	0.5	245	−201.5
−6	−166.67	86.17	−1	0.5	466	−166.3
−7	−142.86	73.86	−1	0.5	733	−141.3
−8	−125.00	64.63	−1	0.5	941	−127.3
−9	−111.11	57.44	−1	0.5	1306	−110.6
−10	−100.00	51.70	−1	0.5	1528	−103.1

Note: The thickness of plano-concave lens and plano-Fresnel lens are 2 mm.

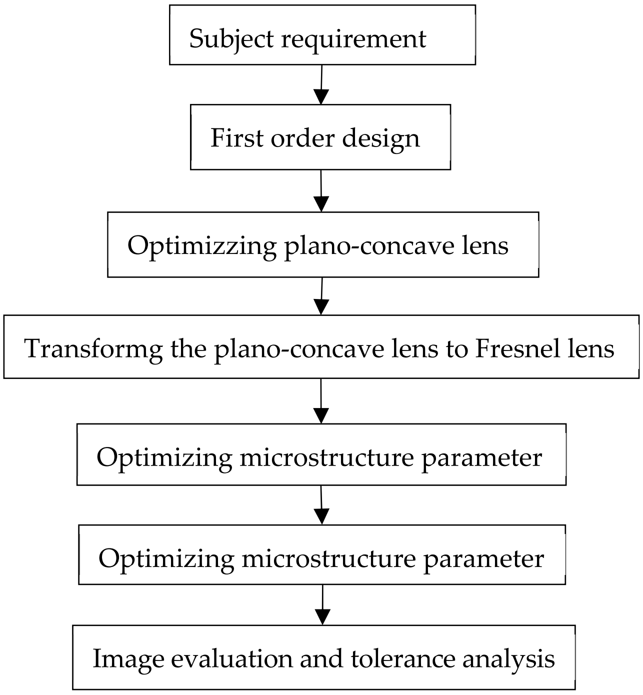

Figure 2. Flow chart of Fresnel lens for swimming goggles design.

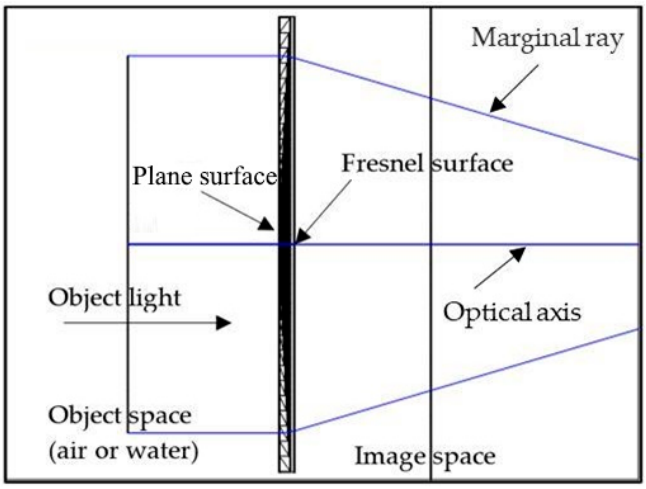

Figure 3. The cross-sectional structure of the Plano-Fresnel lens of swimming goggles [7].

4. Conclusions

The purpose of using a Plano-Fresnel lens for vision correction instead of a plano-concave lens is to solve the refractive power change in swimming goggles in the air and water. For people with high myopia, the thickness of the goggle lenses' edge is too thick and too heavy, and the production yield decreases. The product was designed with an innovative method that was used in this study and avoided the above problems. The thickness of the lens' edge was the same as that of the center. In this study, the lens' diopter of the swimming goggles was calculated by satisfying the object space of water and air at the same time. Afterward, the spherical optical surface of the plano-concave lens was calculated and converted into a Fresnel surface. Finally, the microstructure of the Fresnel surface was optimized using the optical design program. During this process, the lens's diopter of the swimming goggles in two different media was highly close to the same value. The simulation results were compared to those calculated with the lens maker's formula and the error of the two data was within 5%, which is acceptable for swimming goggle lenses.

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