

Novel Retroreflective Micro-Optical Structure for Automotive Lighting Applications

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ABSTRACT

Retroreflective (RR) optical elements play a critical role in signaling, safety, and aesthetic/styling functionality of automotive lighting. The commonly-used inverted corner cube (ICC) RR structures with hexagonal aperture have several critical limitations that are primarily rooted in their manufacturing technique that involves complex assemblies/shapes of hexagonal pins and electroforms, particularly in case of freeform surfaces. This study introduces a novel RR micro-optical structure, namely: right triangular prism (RTP). The geometric model underlying this new geometry is defined as the intersection between a cube and a plane placed in a particular relative orientation with respect to each other. Following this, non-sequential optical simulation studies were performed analyzing the effect of incident light orientation. Advanced optical functionality of the RTP with a width of 450 μm was obtained as practically unattainable through conventional hexagonal pin-bundling technology. The study also shows that the use of RTPs can overcome the design/optical performance limitations associated with traditional ICC RR designs. Furthermore, the newly-developed single point inverted cutting technology was introduced as a feasible mean to fabricate functional optical prototypes and/or tooling inserts. In this regard, samples of functional RR areas were produced on flat PMMA plates and their preliminary validation has confirmed a 57% increase in the optical performance of the RTP compared with conventional ICC RRs. This supports the feasibility and/or potential of RTP as a new RR option for automotive lighting.

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INTRODUCTION

Retroreflection is an optical phenomenon that allows the light to be reflected in a direction that is parallel to that of the source [1]. This optical property is used in a wide range of applications including, but not limited to: metrology, military as well as automotive industry [1]. By contrast with the wide applicability of RRs, the present study is solely focused on the use of the retroreflectivity in automotive industry, with a particular emphasis on rear and side lighting of the vehicles.

Retroreflection is conventionally achieved by means of passive optical elements called retroreflectors that could be of three main types: lens and mirror, corner cube (CC) and inverted cube (IC). The three main types of ICs defined in [2] were: right triangular prism (RTP), triangular aperture inverted corner-cube (TA ICC), and hexagonal aperture inverted corner-cube (HA ICC). All three types of IC can be used for tail and side automotive lighting. The IC RR elements used in the automotive industry are usually generated in a variety of plastic without reflective properties. Hence, in order to achieve retroreflection, all ICC RRs rely on a phenomenon known as total internal reflection (TIR) [3]. All IC RR elements share some

common geometries in a sense that all IC RR should be enclosed at least two-three orthogonal reflective facets in order to achieve TIR and thereby retroreflection [2].

This work expands further the development of the IC RR geometries and clarifies how each of those geometries can be obtained from a single unit cube. Further, the present study places a particular emphasis on a specific type of IC RRs called RTP whose possible fabrication methods and optical performance are analyzed in detail. While the optical performance IC RR could be assessed by means of various criteria such as: retroreflection efficiency (RRE), brightness, angularity and divergence [3], the present study has solely focused on RRE as most critical metric for automotive industry.

OPTICAL FUNCTIONALITY AND GEOMETRIC MODELING

To fulfill their rear and side lighting functions, the ICC RRs used in automotive industry consist of two elements: i) the RR element with a primary role in safety and ii) the illumination element with role in

illumination during signaling, braking, etc. [2] The RR elements in the RR tailgate are placed in an array capable to reflect the light back to the succeeding traffic to ensure that the preceding vehicle is visible. On the other hand, the illumination element consists of a generally large slab-like structure that essentially holds individual RR elements together in the array. The illumination element allows the passage of the light generated by the preceding vehicle for the purpose of signaling and braking and also positions the individual RRs in a 3D array that matches the external styling of the car. To illustrate these concepts, Figure 1 depicts the RR and illumination elements of an ICC RR that belongs to the tailgate.

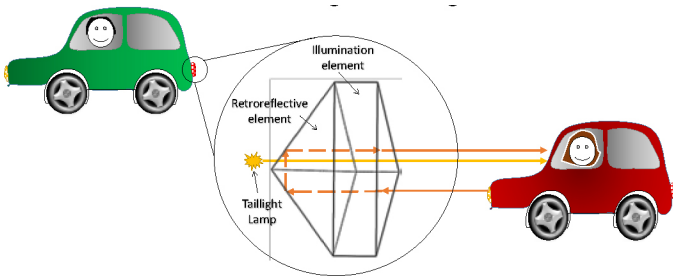


Figure 1. Retroreflectors: optical functionality and structure

It is important to note that these two functionalities (illumination and retroreflectivity) do not operate simultaneously and therefore do not optically compete while the external shape of rear and/or side lighting has to fit the general styling of the vehicle to which they belong to.

To address just its retroreflective function, a typical taillight RR element should consist of an incident facet through which light will enter/exit and at least two orthogonal reflective facets capable to successively deviate and then return the beam in a direction parallel with that of incidence (Figure 2). The fascicle of incident/incoming light will first pass through the illumination element and then will access the RR element through its incident facet. After that, the light will hit first and second reflective facets respectively, and they will successively deviate the fascicle according to TIR laws. After the contacting the second reflective facet, the light is redirected to the incident facet and passes again through the illumination element before being released to the environment. Because of the double TIR, the incident and emergent rays are parallel and this represents in fact the essence of retroreflectivity.

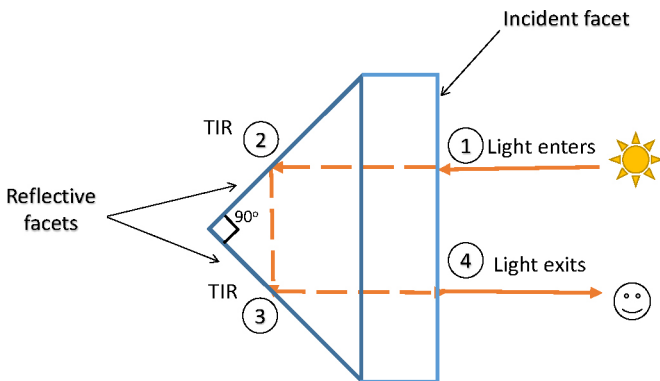


Figure 2. Working principle of a typical TIR-based RR element

From a geometrical standpoint, all conventional ICC RRs can be generated by means of a cube of a particular orientation that is trimmed off with a plane of a certain orientation and position relative to the cube. The retained corner of the cube provides the required retroreflective functionality of the element generated in this manner.

The commonly used in automotive lighting ICC RRs can be modeled as a result of two consecutive geometric transformations/operations (Figure 3). Initially, a unit cube is positioned with the bottom-rearleft A vertex at $\{0, 0, 0\}$ and sides parallel with principal X, Y, and Z axes of the coordinate system. After that, the unit cube is rotated around the vector $\mathbf{n} = \mathbf{Z} \times \mathbf{V}$, with an enclosed 3D angle of $\tan^{-1}(\sqrt{2}) = \theta = 54.74^\circ$, in such a way that the main diagonal of the cube (e.g. $\mathbf{V}$ or AB direction) becomes vertical.

Vector $\mathbf{n}$ is then normalized to $\hat{\mathbf{n}}$ and its coordinates are substituted in Equation 1 to obtain the rotation matrix $\mathbf{R}$ with which the cube is rotated 54.74° [4]. The general rotation matrix $\mathbf{R}$ about an axis with an arbitrary spatial direction is defined as [4]:

$$\mathbf{R} = \begin{bmatrix} n_x^2(1 - \cos\theta) + \cos\theta & n_x n_y(1 - \cos\theta) - n_z \sin\theta & n_x n_z(1 - \cos\theta) + n_y \sin\theta \\ n_x n_y(1 - \cos\theta) + n_z \sin\theta & n_y^2(1 - \cos\theta) + \cos\theta & n_y n_z(1 - \cos\theta) - n_x \sin\theta \\ n_x n_z(1 - \cos\theta) - n_y \sin\theta & n_y n_z(1 - \cos\theta) + n_x \sin\theta & n_z^2(1 - \cos\theta) + \cos\theta \end{bmatrix} \quad (1)$$

where n_x , n_y , and n_z are the X, Y, and Z components of the normalized vector $\hat{\mathbf{n}}$ respectively, and θ is the 3D angle between the vector $\mathbf{V}$ and X, Y or Z axes ($\theta = 54.74^\circ$).

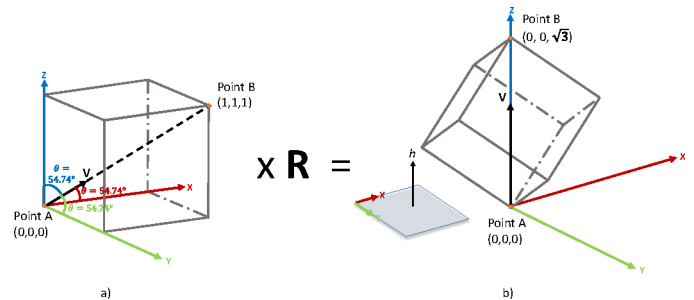


Figure 3. Geometrical definition of the ICC RR: a) original unit cube to be rotated with θ about $\mathbf{n}$ and b) trimming plane ($\mathbf{h} \parallel \mathbf{V} \parallel \mathbf{k}$)

This transformation can be described mathematically as:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \cdot \mathbf{R} = \begin{bmatrix} 0 & 0 & 0 \\ 0.5000 & 0.3659 & 1.1548 \\ -0.2886 & 0.5773 & 0.5774 \\ 0.7886 & -0.2114 & 0.5774 \\ -0.5774 & -0.5774 & 0.5773 \\ 0.2113 & -0.7887 & 1.1547 \\ -0.8660 & 0 & 1.1547 \\ 0 & 0 & 1.7321 \end{bmatrix} \quad (2)$$

where the initial left term encompasses the coordinates of the 8 vertices of the original unit cube. Following the rotation, the unit cube has to be trimmed off by means of a horizontal plane of normal $\mathbf{h}$ ($\mathbf{h} \parallel \mathbf{V} \parallel \mathbf{k}$) that can be positioned at variable distances $h \in [0; \sqrt{3}]$.

between A and B (Figure 3b) to form ICC RRs with different apertures. As Table 1 shows, the shape of the aperture is strongly dependent on the location of the trimming plane (a represents the side of the cube).

Table 1. Dependence between ICC RR aperture geometry and trimming plane location

Aperture Shape	Cutting Plane Height
Triangular	$0 < h \leq a \frac{\sqrt{2}}{2} \sin \theta$
Enneagonal	$a \frac{\sqrt{2}}{2} \sin \theta < h \leq a \left(\sqrt{3} - \frac{\sqrt{2}}{2} \sin \theta \right)$
Hexagonal	$a \left(\sqrt{3} - \frac{\sqrt{2}}{2} \sin \theta \right) < h < a\sqrt{3}$

The aperture of each of the three elements is primarily defined by the number of sides (Figure 4).

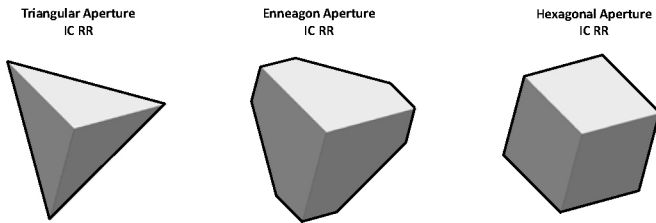


Figure 4. Top view of the three main ICC RR

As discussed above, the retroreflectivity of all RR elements stems in the mutual orthogonality of their internal reflective faces as well as the TIR phenomenon. Because of this, a new design option for RRs could involve a right triangular prism (RTP) to be formed by two geometrical transformations of the unit cube: i) -45° rotation around X -axis to be followed by ii) scaling the length along Y -axis. These transformations are depicted in Figure 5, where $\mathbf{R}_X$ is the rotation matrix about the X -axis and $\mathbf{S}_X$ is the scaling matrix in the X -axis. Equations 3 and 4 show the rotation matrix about X -axis and the scaling matrix in the X -axis, respectively.

$$\mathbf{R}_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & -\sin \beta \\ 0 & \sin \beta & \cos \beta \end{bmatrix}, \quad (3)$$

where $\beta = -45^\circ$, and

$$\mathbf{S}_X = \begin{bmatrix} s_x & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (4)$$

where s_x is the scaling coefficient by which the rotated cube could be enlarged ($s_x > 1$) or shrunk ($s_x < 1$), as required.

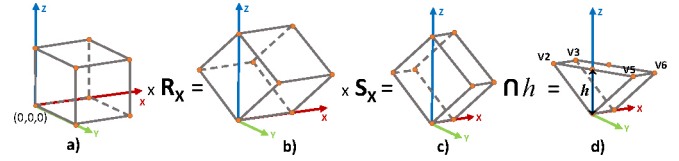


Figure 5. Geometrical definition of the RTP: a) original unit cube; b) rotation with β around X -axis; c) scaling along X axis and d) horizontal trimming of the unit cube

These transformations can be modeled as:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \times \mathbf{R}_X = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.7071 & 0.7071 \\ 1 & 0.7071 & 0.7071 \\ 1 & 0 & 0 \\ 0 & -0.7071 & 0.7071 \\ 1 & -0.7071 & 0.7071 \\ 0 & 0 & 1.4142 \\ 1 & 0 & 1.4142 \end{bmatrix} \times \mathbf{S}_X = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.7071 & 0.7071 \\ s_x & 0.7071 & 0.7071 \\ s_x & 0 & 0 \\ 0 & -0.7071 & 0.7071 \\ s_x & -0.7071 & 0.7071 \\ 0 & 0 & 1.4142 \\ s_x & 0 & 1.4142 \end{bmatrix} \cap h = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.7071 & 0.7071 \\ s_x & 0.7071 & 0.7071 \\ s_x & 0 & 0 \\ 0 & -0.7071 & 0.7071 \\ s_x & -0.7071 & 0.7071 \\ 0 & 0 & 0.7071 \\ s_x & 0 & 0.7071 \end{bmatrix} \quad (5)$$

where the initial left term represents the matrix of vertices for the original unit cube. After rotation and scaling are completed - same as for ICC RRs - a horizontal trimming plane can be used to generate the final RTP geometry, as illustrated in Figure 5d. It is important to recognize that the added scaling enables the dimensional decoupling of the two sides of rectangular aperture of the RTP that would be dependent in absence of the scaling transformation. Also, while the trimming plane could be positioned virtually anywhere below the middle of the rotated cube ($0 < h < \frac{a\sqrt{2}}{2}$), it was assumed, for simplicity reasons, that $h = \frac{a\sqrt{2}}{2}$.

OPTICAL SIMULATION AND ANALYSIS OF PRISMATIC RR MICRO-OPTICS

As it was found in the previous study [2], RTP is characterized by a retroreflection efficiency (RRE) of 99.994% that is attained when the incoming beam enters the element at a 0° incidence angle (e.g. perpendicular to the plane of the aperture). However, when the angle of incidence deviates from 0° , both RRE and distribution of the retroreflected light are completely altered. To further analyze this, a single RTP element was optically modeled and three different scenarios were investigated:

1. RTP without illumination element
2. RTP preceded by a $100 \mu\text{m}$ thick illumination element