

ABSTRACT

We present an efficient and effective collimating lens system for LEDs. It consists of two lenses: an immersive ball lens within which an LED die is optically bonded, and an adjacent collimating lens that produces uniform illumination at its output plane. The three surfaces of the system are numerically tailored in accordance with the angular distribution of light emitted by the die. When the immersion lens is surface-tailored, the resultant shapes are sufficiently close to a spherical surface that the manufacturing convenience and low cost of an exact sphere make it the preferred shape. The immersion ball-lens reduces the angular spread of the LED's light from $\pm 90^\circ$ to $\pm 60^\circ$ in air. The bottom surface of the collimating lens redirects each light ray to its proper place (axial radius) in the output beam, at which point the top surface redirects the ray to become parallel to the optical axis. Uniformity of output illuminance occurs when a ray's proper place is determined by its place in the cumulative angular distribution near the immersed source. Three surfaces suffice to give highly efficient collimation as well as spatial uniformity of the output beam.

Keywords: collimating backlight, LED, immersion lens, tailoring, illuminance-uniformity, RGB beams

1. COLLIMATION OF LED LIGHT

Collimation will here denote the confinement of a source's light to a relatively narrow beam, about a tenth of a radian, or less than $\pm 3^\circ$. Near the system aperture, illuminance within the beam is the product of the solid angle subtended by the source's image and the luminance of that image. This near-field condition is met wherever the source image is smaller than the solid angle of the system aperture. Thus the near field of an LED collimator extends a distance ten times the system-aperture diameter, at which juncture the beam diameter has only doubled. This leaves room for such devices as projection lenses and beam splitters.

The latest (mid-2001) die attain impressive luminance levels, above 100,000 foot-Lamberts, by design accommodations to a formerly neglected factor, heat transfer out of the active layer, in order to keep its operating temperature below 125°C . For an additional performance enhancement, transparent substrates promote side emission, so that the source etendue covers a

full $\pm 90^\circ$. Some designs surround such die with a specular reflector. Demanding applications motivate the use of the entirety of this side emission. As shown next, currently available collimation solutions are less than satisfactory for LEDs.

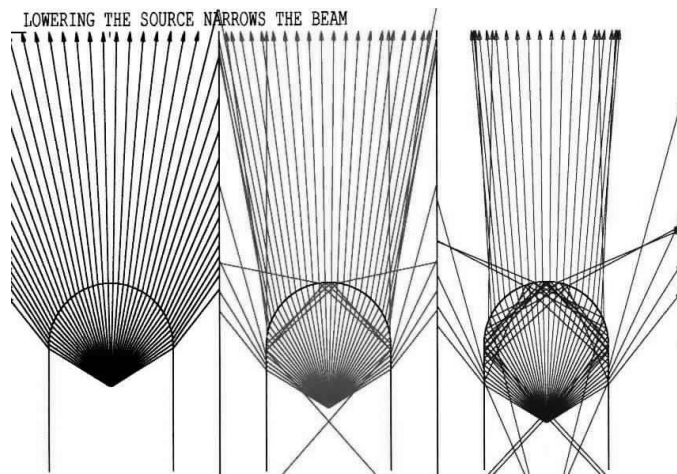


Figure 1. Bullet lens with die-in-reflector source. Left, all light gets into wide beam. Center, narrower main beam with skirts and internal-reflection losses. Right, narrowest beam has greatest losses.

1.1 Bullet lenses

The most prominent commercial package for LEDs is the bullet lens. This easy-to-manufacture shape consists of an epoxy cylinder and hemisphere, the latter doing the beamforming as a simple spherical lens. With a single refracting surface, no tailoring is

possible, and the maximum bend angle is only 30° . Although the $\pm 90^\circ$ of LED output is reduced by a reflecting cup to $\pm 60^\circ$, this cup is typically more matte than specular, so that its luminance is far less than that of the die. The lensing action of the dome can only make a $\pm 30^\circ$ output in air. In order to get narrower output, the die must be moved away from the dome, although this reduces efficiency due to total internal reflections by the dome. Figure 1 shows three source-positions within a bullet lens. Lowering the source reduces the light in the beam while narrowing it. The narrower the output beam,

the less efficient the collimation. Although a commercial success, the bullet-lens shape is quite suboptimal, from an optical standpoint, without even considering the typically poor optical quality of the lens surface. Its only redeeming feature is that it is an immersion lens, taking advantage of the refractive index of epoxy to reduce Fresnel-reflection losses and widen the critical angle within the die. Nonetheless, optical efficiency from die to output beam is typically only 50%, partly due to total internal reflection by the dome, which sends light backwards. This is shown in Figure 1 on the right.

1.2 DTIRC¹

The dielectric totally internally reflecting concentrator has the advantage of being much shorter than a reflective compound parabolic concentrator. It is suitable for immersing LEDs, but has two disadvantages. Narrow beam width requires excessive device length. In addition, expense is increased by the need for a reflective coating near the LED. This is because an all-TIR version is possible only for refractive index above 1.8, beyond the range of current injection-molded optics.

1.3 TIR lenses²

These are faceted lenses utilizing total internal reflection to collimate the $\pm 90^\circ$ of hemispheric light from a ‘globbed’ die. Figure 2 depicts such a system. Efficiencies of 70% have been attained, but two practical limits seem to prevent any greater efficiency. The tips of the multiple facets will inevitably have finite radii, causing scattering. Injection molded parts typically have tip radii that rarely get under 0.001”. The attendant scattering losses, on a percentage basis, are twice the ratio of tip radius to facet depth. In Figure 2, facet depths range from 0.016” to 0.22”, giving nearly 10% losses.

There is another type of scattering as well, by the totally internally reflection face of the facets. Surface roughness at 10 nanometers r.m.s. causes a few percent of incident radiation to be diffusely scattered, but at 25 nm (a millionth of an inch) scattering losses can exceed 10%. The best diamond-turning surfaces can produce the requisite 10 nm roughness, but many do not. When the scattering is actually visible to inspection, efficiency is poor.

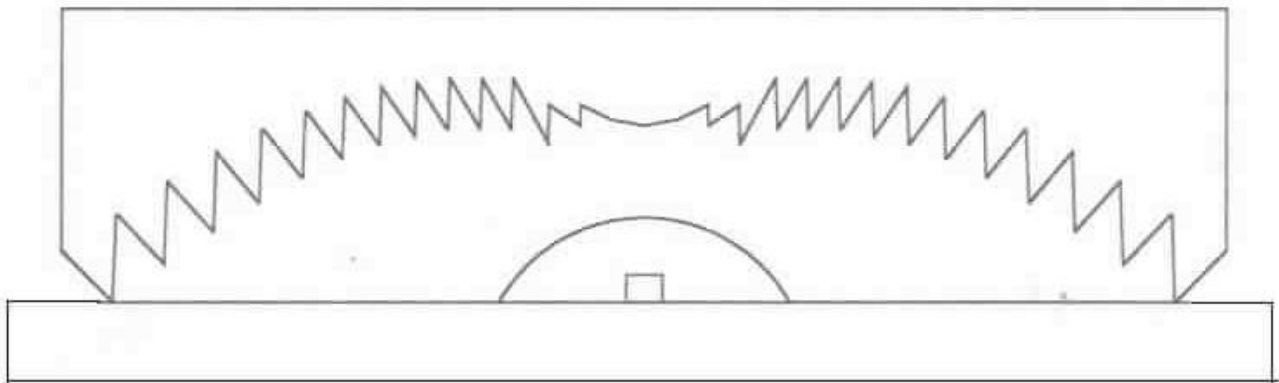


Figure 2. Collimating TIR lens with LED at focus. Ellipsoidal epoxy ‘glob’ encloses the die, providing index-matching..

2. COLLIMATION WITH UNIFORMITY

Collimation began with nineteenth-century ‘lime-light’ stage devices. Electric light bulbs were soon married to parabolic reflectors to make ‘spot lights’. With a single reflecting surface, however, only the overall luminaire size is a free variable: enlarging it correspondingly narrows the beam., but the spatial distribution of flux across the beam is determined only by the luminance distribution across the source. When the beam has expanded into the far field, non-uniform illuminance is acceptable if the variations are smooth and structureless.

Just above the system aperture, however, illuminance is not only non-uniform, but may have distracting image structure as well. There are numerous applications, particularly image projection with liquid-crystal displays (LCDs), concerned with the spatial distribution of illuminance across the beam. Of the abovementioned devices, bullet lenses are typically too small and rough-surfaced to offer suitable near-field illumination. DTIRCs cannot be tailored for uniform illumination, and are impractically long. TIR lenses can be augmented with a ‘mushroom’ lens³ that will give uniform output illuminance, except for small-scale variations on the scale of the facet size. Smoothing these out requires that some propagation space be

allotted to a pair of diffusers, which inevitably reduce system efficiency and increase the beam width. Figure 3 shows such a TIR lens system. While it does produce uniform illuminance, it falls short of theoretically maximum performance levels, due to inevitable, albeit tiny, dark zones between the facets. The first diffuser is a holographic one⁴, molded in relief on the top surface of the TIR lens. A second holographic diffuser acts as a spatial integrator that erases the pattern noise of the facets. The LCD would actually be nearly in contact with the second diffuser. The projection optics are not shown.

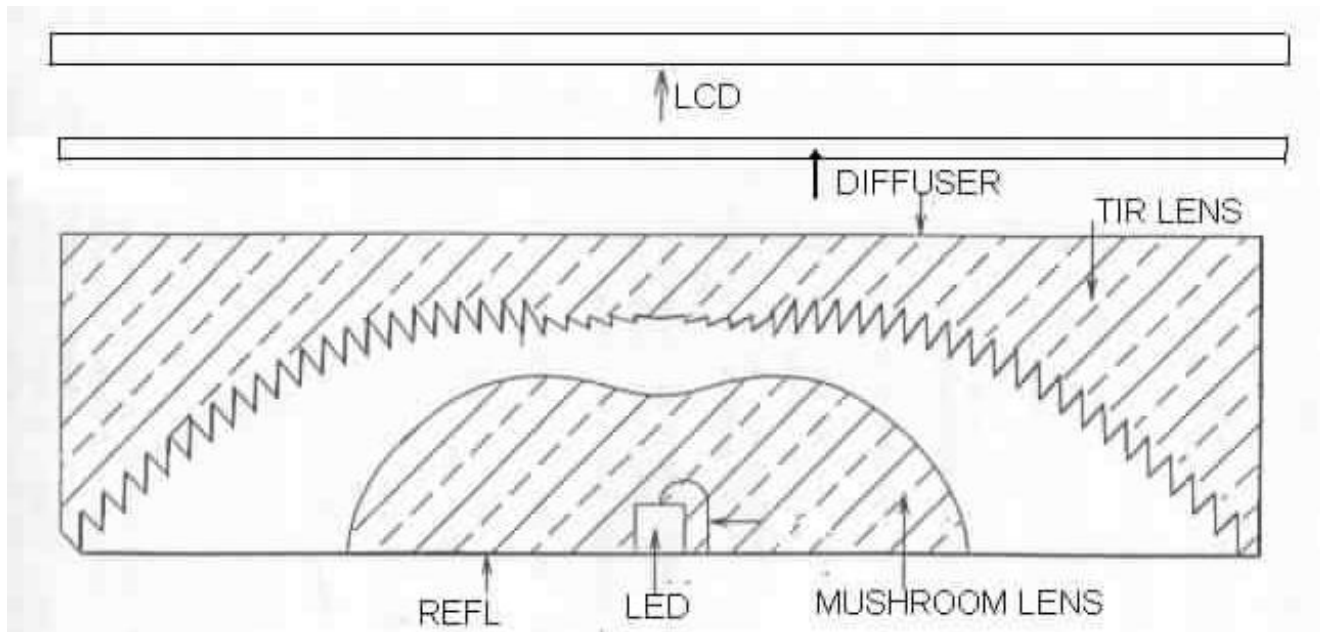


Figure 3. Tailored TIR lens with auxiliary mushroom lens encapsulating an LED die. The exit face of the TIR lens has a narrow-angle holographic diffuser on its surface. Another diffuser is mounted halfway to the LCD screen, where uniform illuminance is attained.

3. TAILORING FOR AN IMMERSED SOURCE

The mushroom lens of Figure 3 has the same overall output emission as the LED, e.g. $\pm 90^\circ$, in that it performs the entire task of rendering the beam uniform. That is, its shape redistributes the angular pattern of the LED source. Its tailored TIR lens performs the entirety of the collimation. In general, TIR lenses can collimate a $\pm 90^\circ$ source, with a lens height only one-fifth the diameter. If more system height is available, however, there is an all-refractive system that will attain high collimation with uniform illuminance, with none of the luminance decrements associated with diffusers.

3.1 Cumulative flux distribution with immersion

The key variable used to design for uniform illuminance is the relative encircled flux. For angle θ from the system axis, the entire flux at all smaller angles is normalized by the total luminous flux F of the source:

$$C(\theta) = \frac{2\pi}{F} \int_0^\theta I(\psi) \sin(\psi) d\psi$$

Thus $C(0) = 0$ and $C(90^\circ) = 1$. The factor 2π is from rotational symmetry about the system axis. Collimation transforms this distribution into a spatial distribution of transmitted flux F' across the output beam. Using a radial coordinate system with r the distance from beam center, the edge of the beam is at $r = R$. The normalized distribution of encircled flux is

$$C(r) = \frac{2\pi}{F'} \int_0^r J(x) x dx$$

With uniform illumination ($J(r) = \text{constant}$), this reduces to $C(r) = \sqrt{(r/R)}$. This means that uniform illumination will be produced when rays leaving the source at angle θ will leave the system at beam radius given by

$$r(\theta) = R\sqrt{C(\theta)}$$

Strictly speaking, the intensity $I(\theta)$ is a far-field quantity, given in lumens per steradian, and assumes a point source for ray tracing. With an extended source, it is only necessary that the edge rays do not deviate enough from the central ray to make Snell's law nonlinear. For example, a 10% increase in internal incidence angle from 30° to 33° increases its sine from 0.5 to 0.54464, instead of 0.55, while a 10% decrease to 27° reduces the sine to 0.454 instead of to 0.45, so that an apparent source size of $\pm 3^\circ$ is definitely acceptable.

3.2 Photometry within immersion lenses

An immersed source requires that the cumulative distribution $C(\theta)$ be for the light propagating within the lens medium. But photometric measurements are typically made in air, in the far field. The solution is to embed the LED in a 2" hemisphere, and then utilize an imaging goniophotometer⁵ for the resultant far-field distribution. This distribution is the basis for a computer-generated rayset⁶ that can be reverse-propagated back into the hemisphere, terminating the rays on its midplane. For a synthetic source, the resultant positions and directions for any desired number of rays, typically from ten thousand to ten million. This emission model can be forward-propagated back to the surface of a test hemisphere within the medium, on which ray statistics can be determined. As long as this test hemisphere is sufficiently far from the source that the source's angular subtense falls in the linear range ($\theta \sim \sin \theta$), then the point-source approximation is valid. In practice, the die should subtend under $\pm 20^\circ$. For example, with large 1mm chips a lens diameter of 3/8" can suffice. This is the size of the first lens in the collimator discussed below.

4. TAILORING THREE SURFACES

4.1 Limits of refraction

Consider that the maximum useful bend angle for a single refraction is 30° , at least in the 1.5-1.6 range of refractive index typical of injection-moldable plastics. In polycarbonate ($n \sim 1.6$) internal and external incidence angles of 34.25° and 64.25° , respectively, are 4.4° from total internal reflection. As seen from the lens surface, the source must have an angular semi-width less than this, at least as seen from the side angle of 90° . Figure 4 illustrates 30° as the deflection limit for polycarbonate. It shows the edge rays from a one-mm blue/green die, 0.15 mm high, immersed in a 3.8" diameter ball lens.

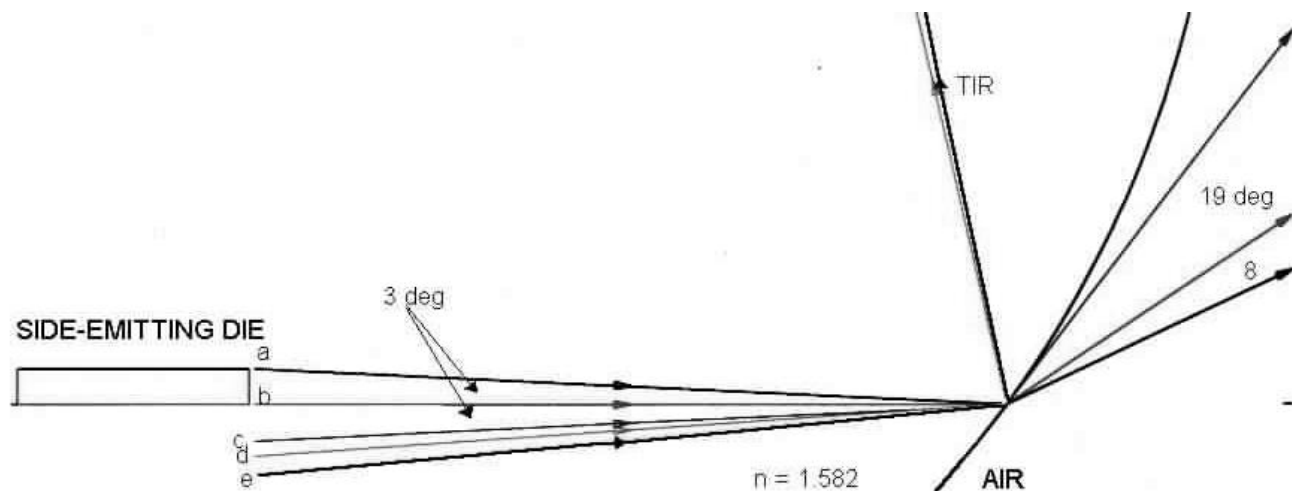


Figure 4. The limits of refraction for immersion within index 1.582 (polycarbonate, red). Ray *a* is deflected 30° . The 3° between rays *a* and *b* is magnified to 8° , while unused ray *c* would exit with a 19° gap from ray *b*. Unused rays *d* and *e* are totally internally reflected.

Conservation of luminance ensures that the 8° in air is filled with the image of the die. The small surface-element through which all these rays pass can be one of a system of circumferential strips that englobe the source, collecting all its light output. Figure 5 shows such a system, on a ball lens, with $\pm 90^\circ$ raysets from the source-center and edge.

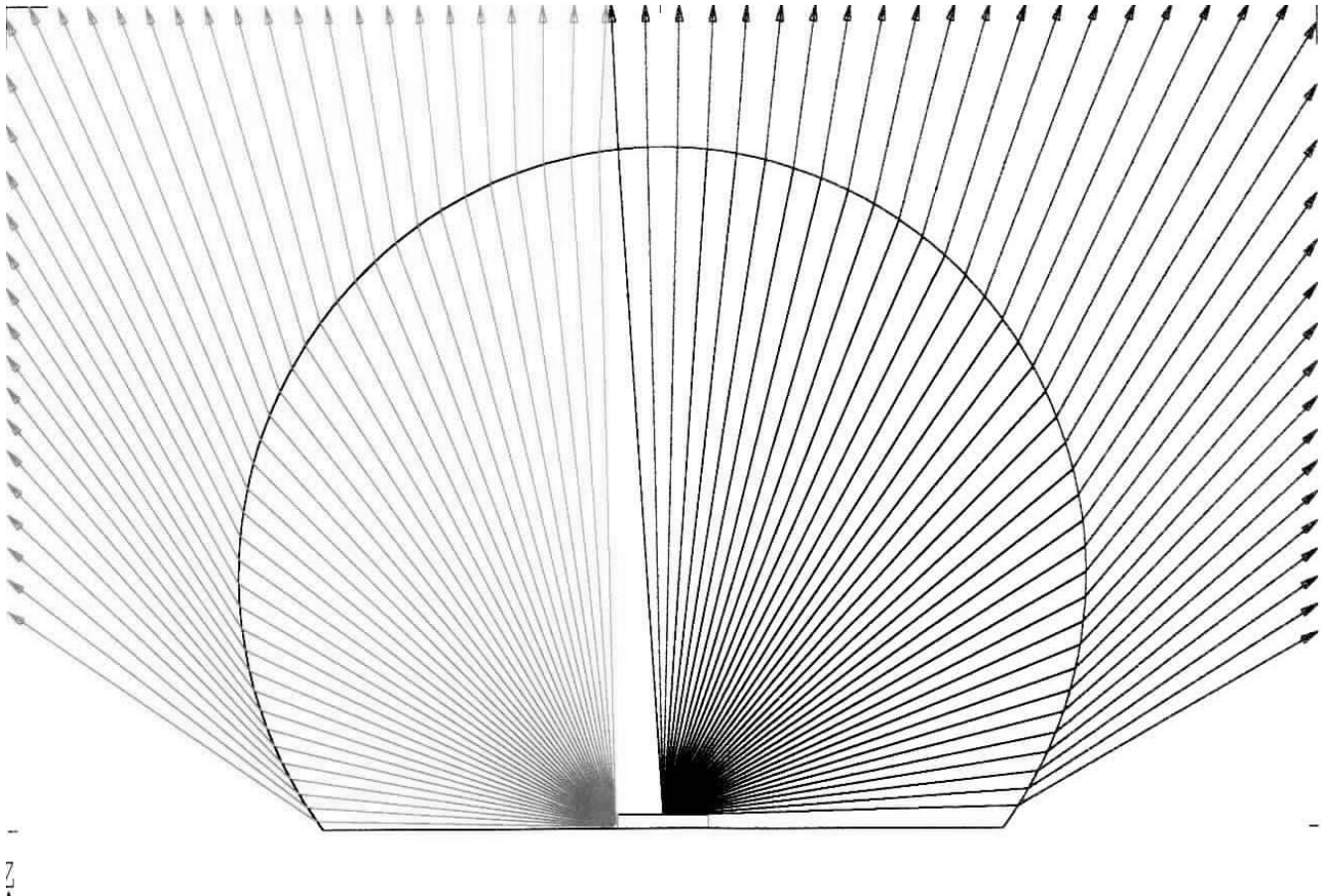


Figure 5. First system surface, 3/8"immersive ball lens, smoothly redistributing $\pm 90^\circ$ LED output, to become $\pm 60^\circ$ in air.

4.2 Immersive Ball lens

Figure 5 depicts the die of Figure 4, radiating from central and edge points. When the actual distribution of luminance around the die is accurately synthesized, then the spatial and angular distribution of radiation leaving the ball lens in Figure 5 can be used to generate a suitable cumulative distribution for use in Equation 2. That is, the ball lens becomes the source to which the second lens is tailored for optimum collection and collimation of this source's output, shown in Figure 5.

Ball lenses are highly favored over any 'parametrically nearby' shapes that require injection molding, which leaves a problematical parting line. Ball lenses, in addition, are low-cost, well polished, and commercially available in many sizes and materials.

4.3 Equipartition of Bends

With sufficient system height, three refractive surfaces can produce bend angles up to the 90° required to utilize all the light from an LED. This means that another lens will be mounted atop the immersive ball lens. At the system edge ($r = R$), the three bends must perform be very nearly equal (i.e., 30°). At all points within the beam, however, there is more freedom to vary the individual bends, as long as they add to the required sum (i.e. θ). This permits the tailoring necessary to attain uniform illuminance, by modest spatial redistribution of luminous flux.

The first case of collimator design, however, can be generated simply by making each of the three surfaces deflect a ray the same amount, $1/3^{\text{rd}}$ the total. Figure 6 shows this lens system as generated by numerical iteration, and it turns out to be an ideal uniform-illuminance collimator for an isotropic radiator. Actual LEDs, however, are never isotropic, tending to have varying amounts of side emission relative to on-axis emission (i.e., normal to the plane of the die's active layer). Tailoring for a non-isotropic source generates lens shapes deviating from the isotropic configuration.

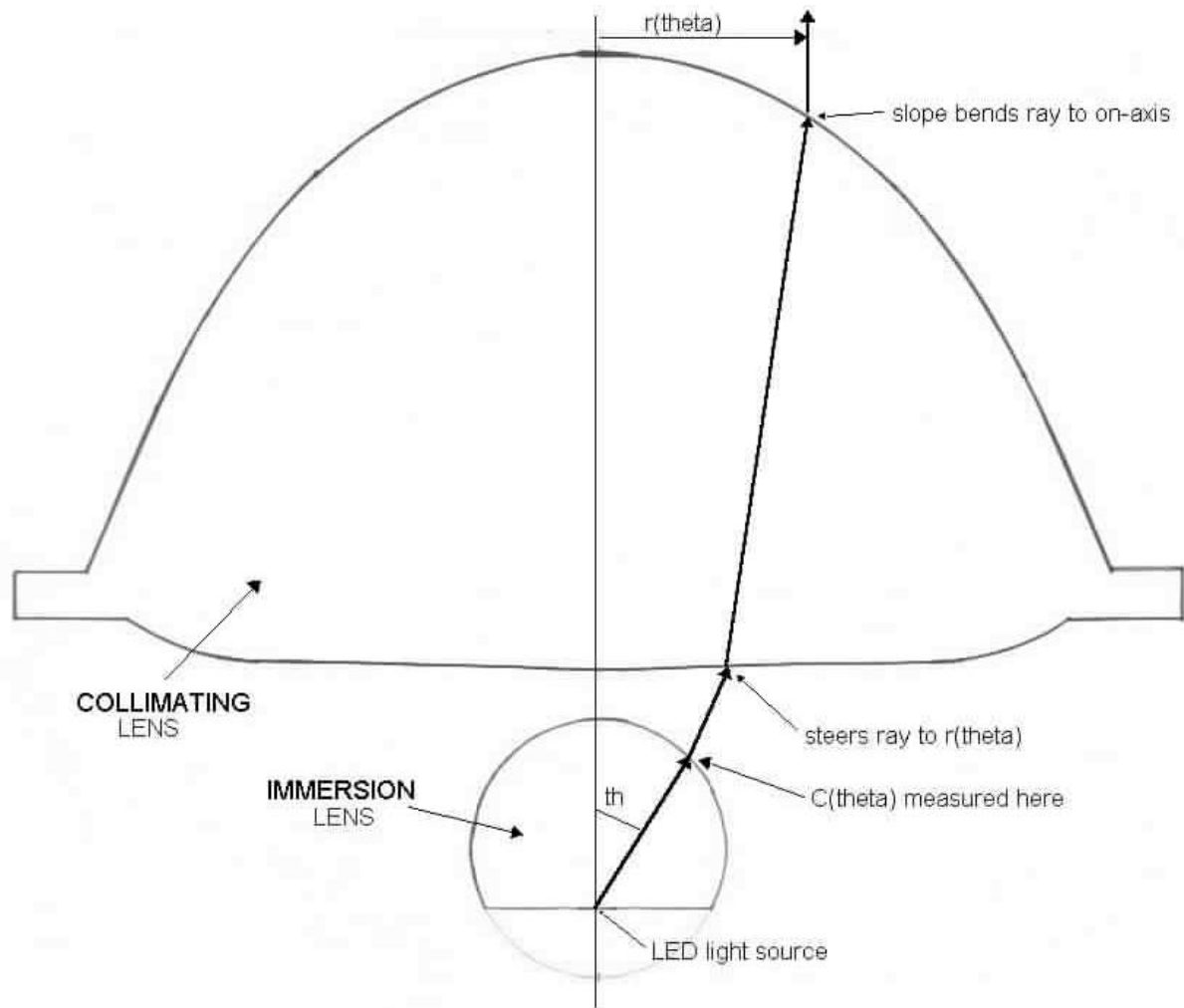


Figure 6. Uniformly illumination collimator system for an isotropic source. For all rays, each lens surface does a third of the total deflection. The shape of immersion lens is very close to a sphere. The source is at the center of the flat immersion-lens bottom. The general method is shown of iterating the lens shape, from $r=0$ outwards. Typically the immersion lens is spherical and nearly touches the bottom of the collimating lens.

4.4 Numerical lens generation

Figure 6 also shows the general method of lens design. The angle θ of a central ray from the axis of symmetry is the index. The iteration is via a small step $d\theta$, which corresponds to a thin circumferential strip around the immersion lens. This strip emits a conical pencil that intercepts the bottom surface of the collimator. At that point, the local slope is adjusted to deflect the pencil to the proper $r(\theta)$ on the top surface. There in turn, the local slope is adjusted to deflect the pencil on-axis.

Figure 7 shows the cross-section of a 1" prototype already fabricated. It will be used in sets of three for an RGB beam-combining system. The system's high degree of collimation is important for such beam combining.

5. APPLICATIONS

This lens system was originally developed for an RGB collimating backlight, which requires tight control of beam uniformity. Thus it is suitable for sunlight-readable LCD backlights in vehicular and portable displays. Its beam uniformity makes it suitable for light-mediated medical applications such as photodynamic therapy. Because of its near-field uniform illumination, this lens system offers the maximum collimation possible at a given aperture. This is important for Raman spectroscopy, where highly collimated beams are essential for filtering out the source wavelength. More general applications are commercial task lighting with an RGB or white LED source, as well as battery-operated LED flashlights.

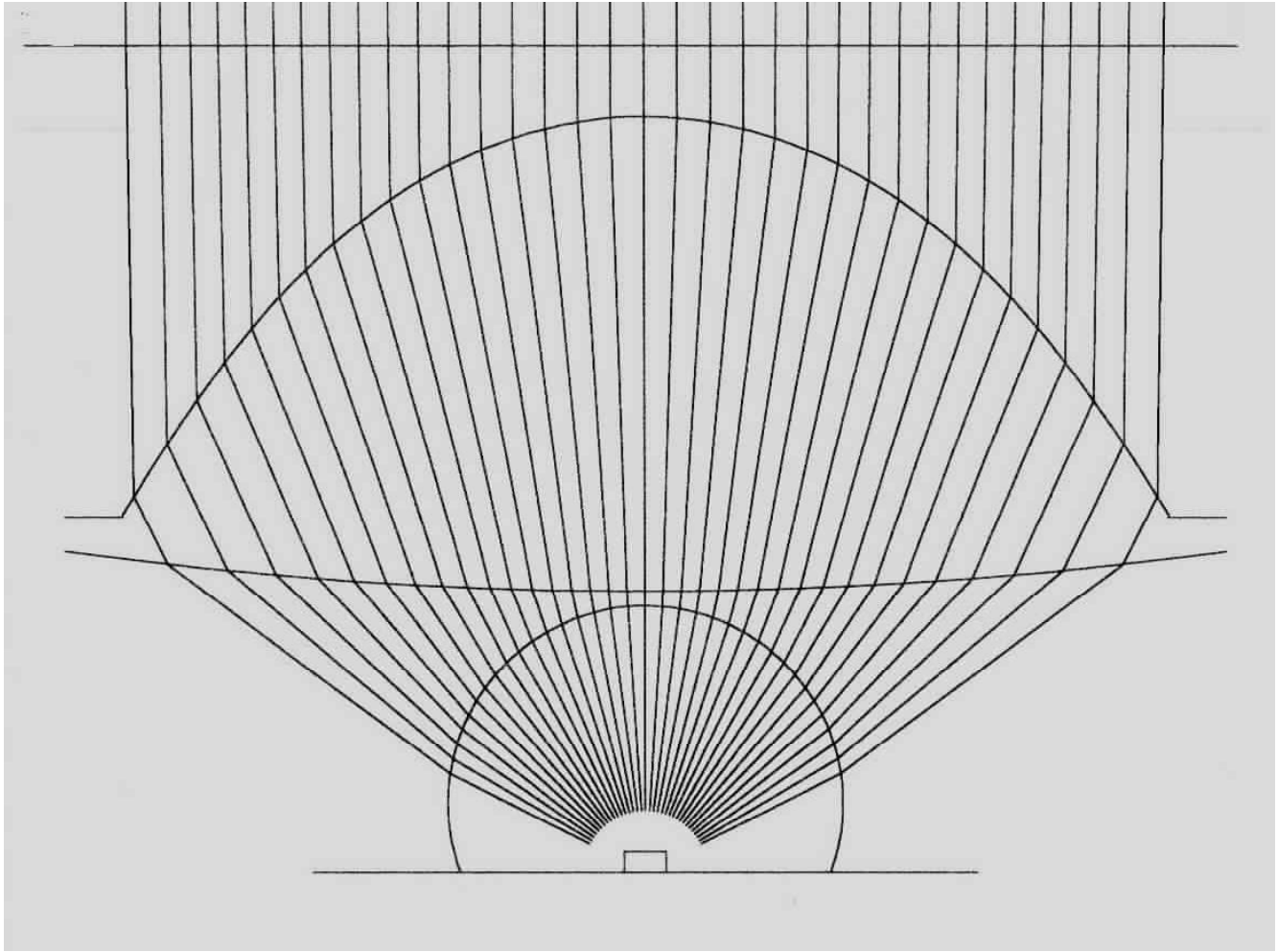


Figure 7. Collimation lens collects light from the ball lens. The collimator's lower surface is nearly spherical, for ease of production. This system does not fully utilize the die's side emission, but did attain its goals of uniformity (10% down in corners) and luminance (150,000 ft-L in blue, 300,000 ft-L in green, 500,000 ft-L in red). Diameter is one inch, the diagonal size of the LCD, which is placed just above the top of the upper, collimating lens.

6. LEGAL NOTICE

Devices revealed in this publication are the subject of United States Patent Applications now pending. Nothing herein shall be construed as any release by the authors of their right to further patent applications in other jurisdictions.

¹ X. Ning, R Winston, J O'Gallagher, 'Dielectric totally internally reflecting concentrators', *Applied Optics* vol 26(20) pp 300-305

² W.A. Parkyn & D.G. Pelka 'Compact non-imaging lens with totally internally reflecting facets', *SPIE* vol 1528, Non-Imaging Optics (1991) pp 70-81

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³ U.S. Patent 5,577,493 by W.A. Parkyn & D.G. Pelka, November 26, 1996

⁴ Physical Optics Corporation, Torrance, California, www.poc.com

⁵ Radiant Imaging Corporation, Chapel Hill, NC, www.radimg.com

⁶ Breault Research, Tucson AZ, www.breault.com, ASAP analysis software

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