Flashlights in lighting simulation

- A technical perspective on the potential of tailored optics

Dr. Andreas Bielawny, Brandenburg GmbH, Technologiepark 19, D-33100 Paderborn

(Taschenlampen in der lichttechnischen Simulation - warum einfach, wenn's auch kompliziert geht?)

Abstract

This paper briefly sketches the world of flashlights and focuses on the optical elements used to create their light distributions from a technical point of view. Classic devices and state of the art products are discussed as well as possible high-end optical setups.
Portable lighting devices, especially flashlights did rarely see the full benefits of technical progress in lighting in the past. This seemed to change with the LED entering the stage. Essentially, flashlights combine all elements of an electric lighting system: light source, optical elements, housing, maybe electronics, and the power supply! Thus, they make formidable objects for technological high-end devices, testing of new technologies, and teaching.
Artificial light is mostly needed in the dark, portable lights used mostly off-grid: far away from electrical power or in times of emergency, or maybe in hazardous environment. Thus, the quality of the light output is often considered of lower importance than the power supply and the robustness. So it is not very surprising that the optical element is often the part that is of lowest technical development level, while the rest of a flashlight may combine a high end microprocessor with some serious styling and almost insane material quality.

The optical setup of flashlights can be tailored to the desired application field with minimum effort: everyday carry (EDC), high range search light (thrower), close range light (flooder), tent or desk light (lantern), police or military flashlight (tactical), or simply the aim of an all purpose light, just to mention some.
In contrast to this situation, most flashlights simply are built around parabolic reflectors without advanced optical functionality (e.g. freeform surfaces), but instead use smooth or rough surfaces (e.g. sanded or "orange peel" surface type). Thus, their light distribution is solely created by the geometry of the system and the quality of fabrication with all consequences.
In lighting simulation, the effect of tailored optics on the light pattern is shown in specific examples. This is backed by selected light samples, if possible during presentation.
A concept study for a high end optical setup is compared with standard off-the-shelf setups.

Flashlights – schematically

Taking a look systematically, any flashlight or battery-powered light combines all elements of artificial lighting: light source, power supply unit, housing, optical unit, and controls; independent of what technical level those elements may have.
The simplest case may be an old-fashioned flashlight with an incandescent bulb (today probably halogen), a simple housing of thin metal and plastic parts, a few cylindrical batteries (C-cells for example) and a reflector with a simple flat protective plastic cover lens. The control element here would typically be a simple electrical switch or a screw to connect battery and source by twisting.

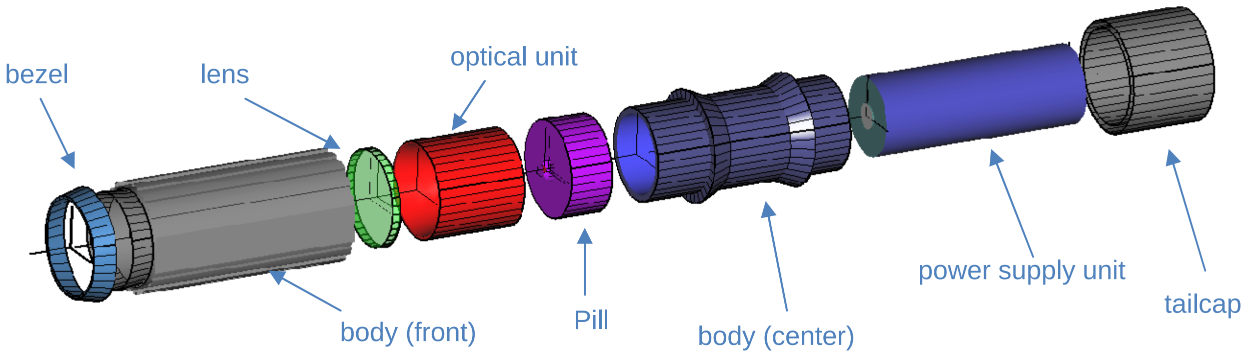


Fig.1: Building blocks of a flashlight: compact LED flashlight with 1865O Li-Ion power cell, reflector setup and single button tailcap; the LED is mounted to a separate component, the "Pill", the optics are protected by a flat front lens.

The same elements in an LED equipped more recent light might be CNC-made aluminum housing, a TIR collimator optics acting as front lens, a clicky switch and driver circuit, the light being powered by any type of battery. This seems to be kind of overdoing, but the LED works best when driven electrically right, and a more massive housing will assist greatly in dissipating the heat from the LED. Thus, an increase in overall quality, material volume and cost should be expected when switching to LED sources in flashlight design.
The design of the housing is done in multiple parts. Especially the socketing of an LED on the so-called "Pill" aims for maximum heat transfer to the large exterior parts (the body), and also into the battery. Even material combinations of copper for the pill and aluminum for the body can be found. Since it is the last part of the construction that influences the light flow, the bezel can be more than just decorative or protective.
Depending on the actual form of the light, these components can of course differ in shape and arrangement.

Power supply unit

The heart of the flashlight is the power supply unit (psu), which is often referred to as battery. There is a wide range of primary (single use) and secondary cells (rechargeable). In today's flashlights, rechargeable Lithium cells are often being used for their high energy density (Wh/m³ or Wh/kg), quick charging capabilities, high output current, and high voltage. On the other hand, primary cells with high availability are still the first choice for a lot of flashlights. Arguments for the latter range from "rarely using the light" (self-discharge)

- to not having a power plug for reloading your batteries in the wilderness. The cost of a battery charger seems in some cases not justified. Batteries come in a variety of formats and size, ranging from small coin-sized cells up to lantern batteries or lead-cells for older industrial portable lights. Battery-packs of multiple cells can deliver higher voltages or increase capacity. It is quite probable that for every battery we might find a flashlight that uses it.

Typical examples for power cells are the classical cylinder cells of primary alkaline type or of rechargeable NiMH or NiCd type. Primaries offer mostly 1.5 V of voltage, rechargeables 1.2 V. Most interesting about Lithium-ion cells is their high voltage of about 3.7 V (V_{OC} = 4.2V when fully loaded). This matches the voltage range of most white LEDs very nicely. Cylindrical cells of this type are specified in their dimensions by diameter, length and Form. For example: 1865O reads 18 mm in diameter / 65 mm long / letter "O" for circular cross-section. The cell 1450O is the same size as the famous AA (mignon) "Walkman-battery", but offers more than twice the voltage. Besides these rechargeable Li-cells, there is a variety of lithium primaries, for example the Li-MnO2 type with typically 3 V of voltage, the cells of CR123 (same size as 1634O) type are well known for usage in photocameras; or the Lithium- Tionylchloride cell (Li-$SOCl_2$) which offer very high capacity, low self-discharge, and good temperature range for operation at 3.7 V of V_{OC}.
If different types of batteries with different electrical properties (voltage, maximum current) fit into a flashlight mechanically, a smart control unit can recognize the type of battery being inserted and use an optimized regulation. If that is not the case, it is important to either prepare the driver to handle the possible voltage range, or to make sure that the user knows what to do. This directly takes us to the topic of driving the LED and controlling its output.

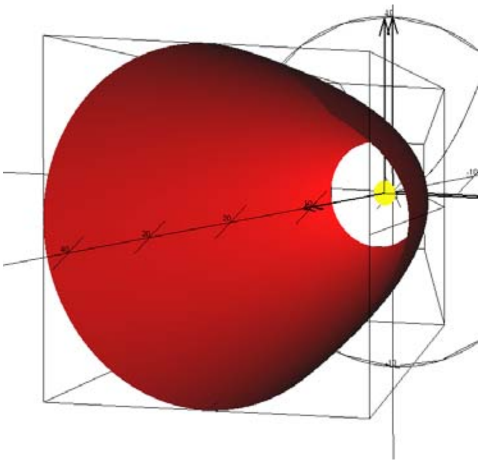
Driver and Controls

Switching on and off can be as simple as it was before LEDs were used in flashlights. Closing the electrical circuit between battery and led is enough. However, the nature of the LED as a solid-state semiconductor component demands more than that if we want to create a good lighting setup that not only benefits from the peculiarities of the LED but makes sure its needs are taken into account.

The driver is an electronic component that feeds the LED with the right amount of power or current at a befitting voltage. Depending on the actual parts used to create this circuit, it may require certain ranges of voltage for the PSU or the LED and can have a maximum current until it shuts down or will be destroyed by thermal effects. Drivers for flashlights differ not much from those in general lighting or automotive design. They have to be fairly small though, and will not get a chance for good power dissipation due to the small size of the whole part itself. A good driver will be efficient to preserve energy and keep the thermal power loss on lowest levels possible, while simple (and cheap) drivers will just "burn" excess voltage in a resistor and in consequence will generate nasty amounts of heat. The LED needs to be driven "cold" enough (at low currents) to be in balance with the heat transport the housing can offer, if stable output levels are desired. In most cases there are only 2 ways of getting heat out of the flashlight: 1) convection and airflow when moving, and 2) the hand holding it. If the LED produces too much heat, temperature goes up, the light output is being decreased, the color may change. At higher temperatures, the output and lifetime of the LED degrade irreversibly. Compensating this effect by increasing the power supplied to the LED to get the output back to the selected level makes it worse for the LED, and only offers a short-term solution for keeping the flux high, with the diode ultimately facing thermal death. Sophisticated control units monitor the temperature of the LED, maybe even of the battery and housing to regulate the power to the LED within safe limits.

The possibility to dim the LED's output down to output levels far below than the maximum level is a key feature in modern LED flashlights, or rather one of the major advantages of the LED in general. Being able to look for the lost keys in the grass without ruining your night vision by switching to a moonlight-leveled minimum mode seems a little exotic, but for the military, outdoor activists or observations, such feature can be essential. A medium dim mode could offer the best ratio of light output and battery lifetime for an all-purpose light, while a low mode can be the last chance to keep the light running until sunrise or in emergency situations.
The potential of dimming has been of such a high impact on the application width of a single flashlight, that it has triggered the development of a variety of user interfaces (UI). Those are primarily designed for certain user groups and applications fields but user Interfaces for flashlights can technically also be classified by on/off switching methods and by mode selection methods. Is On/Off executed by click or by twist? Is the mode selection performed with a single button (that also is responsible for On/Off) or are multiple controls being used? Is there a magnetic ring selector to scroll through the dim levels?
All kinds of combinations may be used. One example can be a tactical light with a simple "forward" On/Off clicky that is capable of "momentarily on" (morse code functionality) where the available two dimming levels can be selected by twisting the head of the light loose by 45° or fastening it. Some lights make use of two or more controls, while others may use only a single button to do everything by code sequences, e.g. double-clicks.

Reflectors



Despite the huge variety of technical aspects in flashlight, there is one common element that can be found in the vast majority of them: Many lights make use of parabolic reflectors. And there are reasons for that.
First of all, it is extremely simple to calculate, being a polynom of second degree. Second, they are maybe the most traditional reflector shape, common knowledge and thus referred to as kind of an inofficial standard. In consequence, parabolic elements can be bought any size and material without the need for elaborate development.

Fig.2: Paraboloid (f=1.2 mm, 21 mm diameter), emitter is a 2 mm² square chip LED), the light patterns are displayed in Fig.3.

The description in geometrical optics mostly reveals that a parabolic reflector throws light from its focal point towards infinity along the optical axis, quasi parallel light. In combination with the usual on axis forward orientation of LEDs, this leads to the most common way of creating light distributions in flashlights: a combination of direct light from the LED and indirect light controlled by the reflector. The direct emission from the LED is trimmed down in space by the frustum of the reflector, front lens, and bezel and is often denoted as "spill". If the geometry of a setup does not change, the direct part of the output won't either. All rays exiting the light directly without interaction with the reflector essentially produce a lambertian pattern (see center pattern of Fig.3). The shape of the reflector creates the indirect share of the emission. This is often referred to as “spot”.

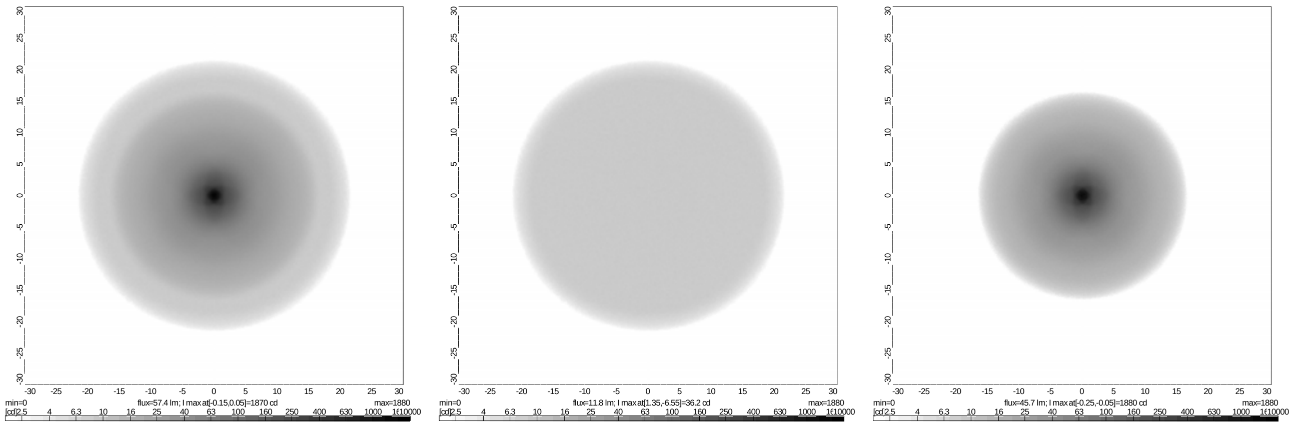


Fig. 3: Parabolic reflector pattern (left), direct light from the LED, the so.called “spill” (center), reflector-controlled pattern “spot” (on the right); intensity display is inverse greyscale .

Defocussing the reflector is sometimes used to apply a certain zoom effect to the flashlight. This has not really been very useful with incandescent bulbs and has not improved with the application of LEDs.

In case that the diameter of the reflector cannot be changed, but a certain spill is desired, there will be a limited depth for the reflector. Instead of living with what we get connecting bottom and top of this zone with a parabola, we can also calculate the reflector curve as a free-form curve, either smooth (PCS) or segmented (PS).
Although the natural light pattern from a paraboloid provides a very smooth cross-section, we can decouple the direct and indirect contributions but will still be able to engineer the indirect part of the light pattern - by giving up the parabolic form.
If we move away from the parabola while keeping the dimensions more or less, any hotspot will become wider, the maximum intensities will drop. This effect can be contained by keeping the parabolic form in certain parts of the reflector, while using different curvatures in others (free-form curves are after all piecewise defined). Alternatively, a change to the surface of the reflector can add light spread and soften or widen the pattern - and this is often done. But engineering roughness for optical purposes is a topic of its own, and this path is mostly followed by trial and error.

Key concept for understanding and creating light patterns on a conceptual level is the model of filament images (or emitter images). Any small enough part of an optical surface may be considered a plane mirror or clear lens micro facet and it would create an image of the light source. Locations on the reflector surface far away from an LED or at very flat angles against the normal of the LED (effective surface area follows cosine) will create small images, closer ones and those in the vicinity of the LED main axis will create large images. Such emitter images can be thought of as stains of light – and all of them together will add up to the complete light pattern.
Among flashlight designers, the two elements created by the reflector are called “throw” for the high intensities at HV that are creating the long range, and “spread” for the components in the pattern that form the transition to the spill and define the fore field intensities.

Freeform surfaces are mainly used to control and manage the distribution of emitter images from certain regions of optical parts. By addressing specific light targets to a certain area of the reflector, the light flux available and the emitter images created in that region can be addressed and directed towards specific parts of the light pattern being built. We can differ simply between faceted surfaces (procedural) and smooth surfaces, which are often of poly-ellipsoidal shape (or more general poly-curve shape, PCS).

In case of **PS reflectors**, the basic shape of the reflector is often still parabolic. It creates the frustum and collects the light. The actual indirect pattern is controlled by the modulation of this surface, the facets. By defining a source position, the facets (pillows) can be calculated automatically to produce the intended spread angles in the far field distribution by finding the required normal vector of the surface in any point.

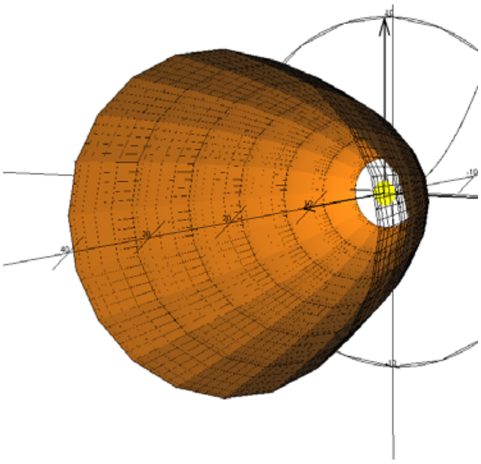


Fig. 4: PS rotational faceted (pillow) reflector on a parabolic base surface shape

Well-known are these reflector types from cold mirror halogen lamps or automotive tail lamps. Their more or less unrivaled strength is the creation of smooth light patterns with a lowered reflector luminance (keyword: “Spiegelrastertechnik”) and a good degree of light control. The light spread from each facet is perfectly suited to iron out color issues from the LED, e.g. from an imperfect phosphor coating, and this property has been very successful in general lighting applications in the past. One drawback however is the complexity for tooling and fabrication created by the pillow optics. Faceted reflectors are used in video camera lights or underwater lights (suited for photographers) and in few flashlight for general purpose.

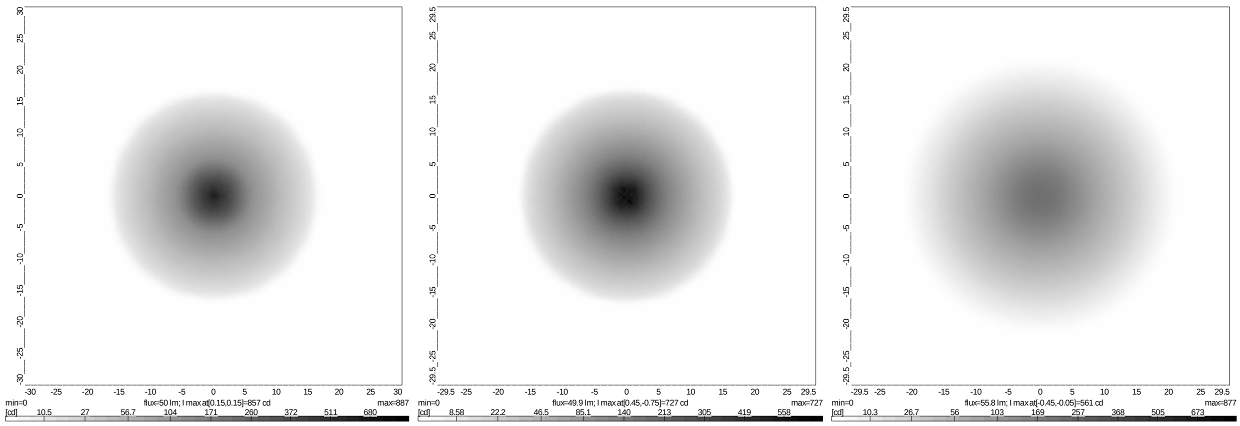
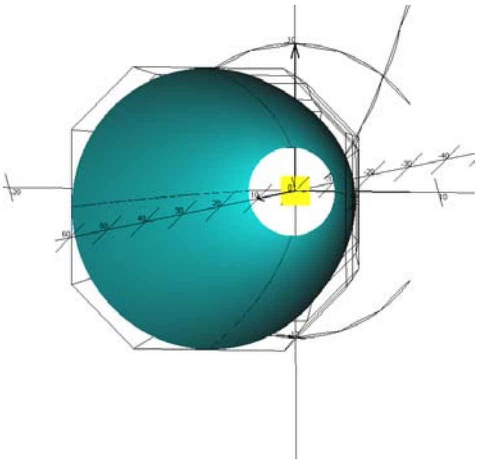


Fig. 5: faceted PS rotational reflector: indirect reflector contribution with mild spreads of 0°,-5° rad / 10°,-10° rot (left), increased spread for a softer and wider plateau-shaped hot spot with spread angles of -2°,2° rad / 15°, -15° rot (center), to almost a medium pattern with increased -20°,20° rad. Only indirect light is shown.



For **PCS type reflectors**, we change the curve of the rotational body, keeping a smooth appearance of the part. Besides the freedom to do so, we can also arrange the focal relations between reflector curve and source. Resetting the focal point of the reflector's curve to a point off-axis can account to certain limits for the extended size of the source itself. After this, the emitter images can be staggered non-paraxial to smooth out the disturbing images of multi-chip LEDs, or to increase the plateau width of a hot spot. With only small variations of the reflector's curvature from bottom to the rim, it is possible to reshape the light pattern for a good balance of throw and spread.

Fig. 6: PCS reflector with smooth surface, built from 4 identical cardinal curves (umbrella wire frame schematics) and with 0° light aiming. The shape is very close to a parabolic reflector

For flashlight development, PCS surfaces can be considered as an upgrade to the parabolic shape. They can create the same range, but offer the significant advantage of tailoring the light pattern completely. Thus, they can compensate peculiarities of the emitter and create a perfect transition from spot to spill. The smooth surface makes sure that fabrication of reflectors is of the same complexity as is it for paraboloids.
For the majority of flashlight developments, PCS reflectors should be able to cover most application fields. CAL software can easily solve the right curve even with customized spread angles.

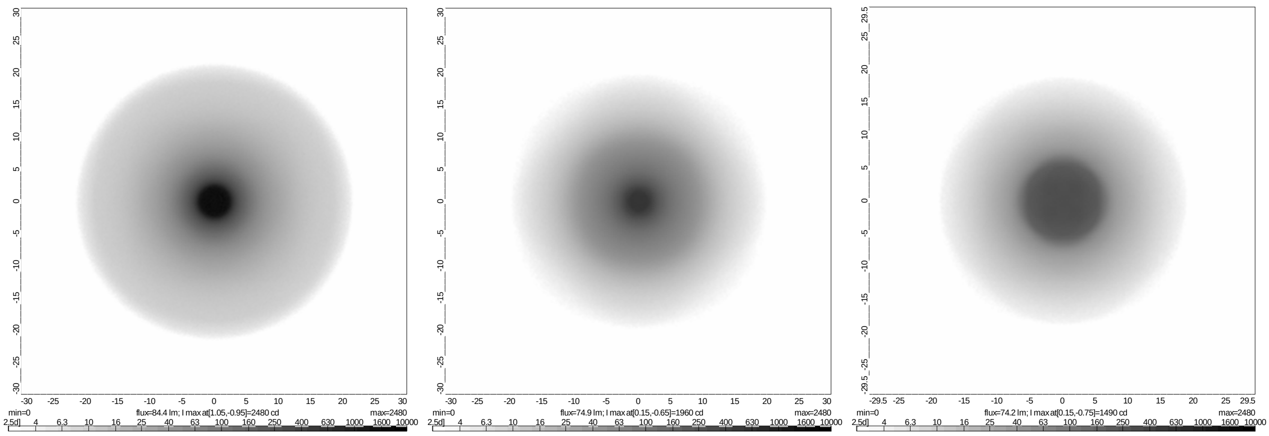
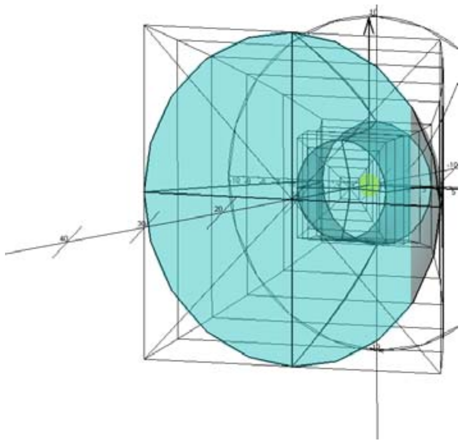
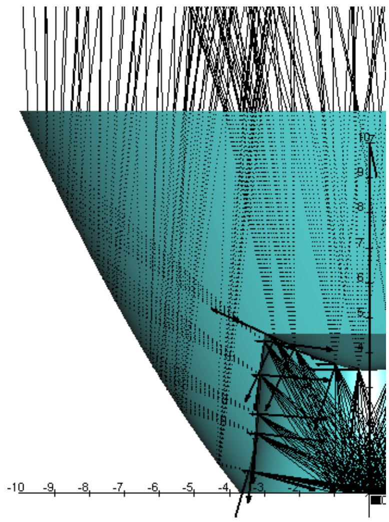


Fig. 7: PCS Reflector on 2mm² square chip LED source model; focusing on HV point from everywhere on the optical surface, with 0° spread along the curve with start aiming at the bottom: 0°, end aiming at the rim: 0° (left); spreads of (5,0), smoothly pasting a medium plateau with large emitter images from the deep regions of the reflector (center); and the inversion of this control function with spreads of (0,5), using the small emitter images from the rim to paint a sharp plateau from -5° to 5°.



TIR collimator lenses are another optical component that can be found in LED flashlights. Mostly being made of PMMA or PC they are not suitable for use with thermal sources, but with solid state lighting, their full potential becomes obvious.
TIR lenses combine refractive and reflective processes and can collect and control almost all of the luminous flux. Light emitted by the LED towards the front is controlled by a lens shape, side-emitted light enters the part through a steep curve and is reflected by total internal reflection at the reflector curve.

Fig. 8: circular TIR collimator lens for a single LED, here with 20mm diameter, using degree 5 nurbs curves.



In combination, this gives us control over the indirect components of the light pattern as before, and it adds control over the so far direct share of the flux by designing the freeform lens accordingly. Collimators can make use of volume-saving cuts and may feature additional optical functions added to their exit aperture (e.g. pillow optics).

Fig. 9 (right): Cross section through the TIR lens: the TI-reflector is aiming at +5° near the source and at 0° at the rim of the part; the lens curve spreads from 0° to -10°. Dashed rays are inside PMMA.

Collimators are possibly subject to strong quality issues, as TIR requires a polished surface, also they show multiple internal reflections. In return they offer the highest levels of light control. A primitive version of the same functionality would be a small lens on the LED, or floating above it, combined with a PCS reflector. Collimators usually require a significantly smaller depth of package than reflectors and can be grouped for LED engines.

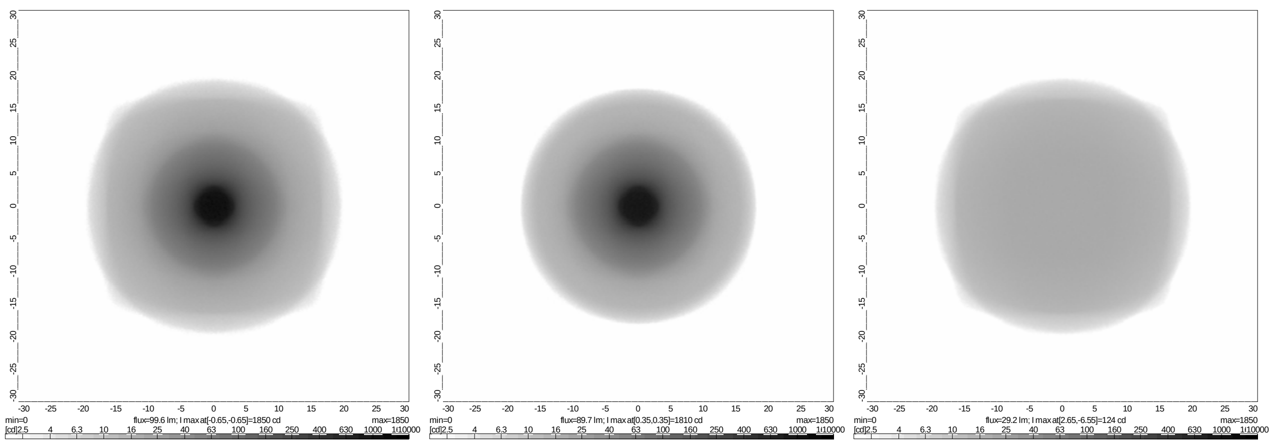
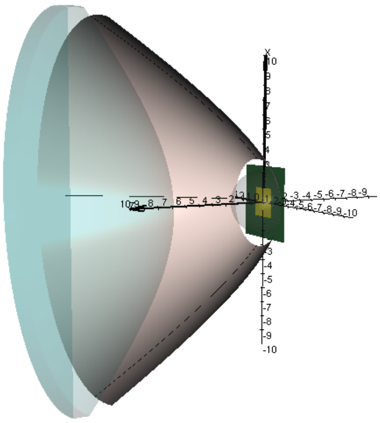


Fig. 10: With spread angles for the lens of diverging (0°,-10°) and for the reflector of converging (0°,5°), the collimator's pattern (left) combines the reflector share (center) with the front lens controlled flux (right). The clear lens transports a magnified image of the chip shape of the source into infinity, due to the linear spread control that is being used here.



Combination optics of lenses and reflectors are often simply patchwork. A paraboloid with an aspheric lens is essentially just a lens with a mismatched reflector. But there are combinations that offer certain advantages.
One example for such a combo optical system is the “minimum depth package”. It features a hyperbolic reflector and a reversely mounted aspheric lens.
The hyperboloid reflector is diverging and creates a virtual focal point (30 mm) behind the LED. Light controlled by the reflector seems to originate from a position deep inside the flashlight. Without a lens, this would be simply a floodlight.

Fig. 11: Combination optics with reflector and lens: minimum depth package without spill.

The focal length of the lens aims at the focal position of the hyperboloid, thus imaging the light from a “far away” source image and making use of a focal length greater than the actual depth (15 mm) of the optical unit. This setup can be considered a long range projector module with a mismatched direct lens imaging component.
Carefully designed, combination optics can achieve a specific pattern at high efficiency, or allow for a smaller packaging volume for the optical unit. In this case, both goals are met, plus the advantage of eliminating all spill and thus minimizing risk of pinpointing the light from off angles. Major drawback of these solutions is cost, accompanied by really small tolerances. The actual size of the light engine reduces the maximum intensity achievable, because there cannot be the tiny emitter images that are created in larger or deeper setups.

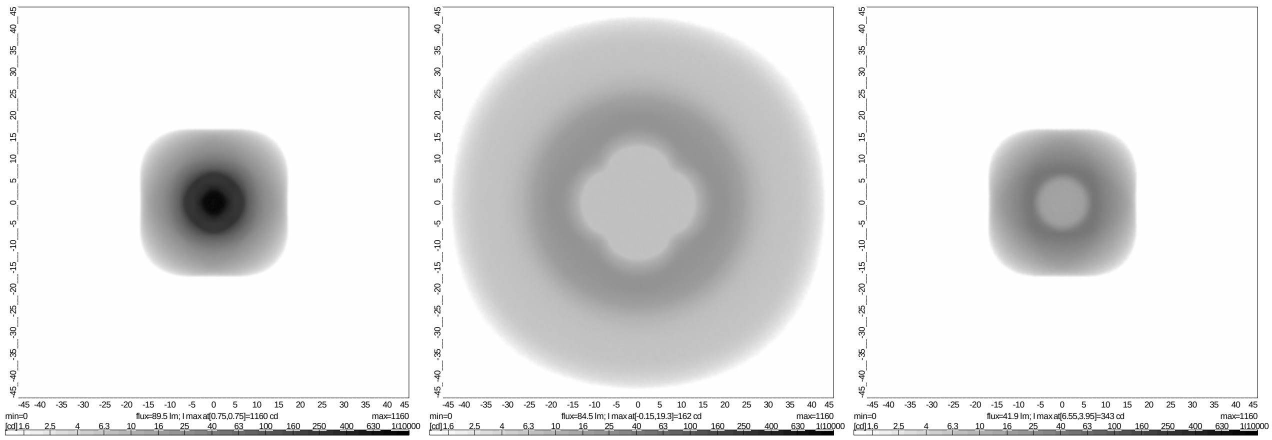
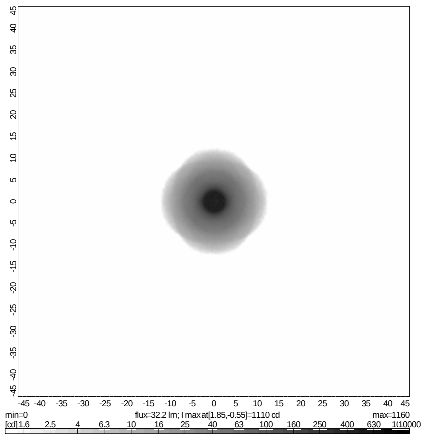


Fig. 12: Combo optic pattern (left) and emission created by the hyperbolic reflector alone (center) and by the lens only (right). The reflector alone cannot create a hotspot, it is of diverging nature; the lens alone can’t achieve that either – it would be simply defocused. There is no intensity outside of this pattern: zero spill.
If the light towards the lens is blocked artificially, only the flux from the reflector is detected after passing through the lens (bottom right), showing the hotspot from the small projection module.



Two Examples

Varta 617
General purpose flashlight

3V incandescent bulb, 2x C-cell batteries, translucent head (red), side switch, single mode: on/off, sheet metal body and plastic head, parabolic reflector (coated plastic)

Fenix TK11
Tactical flashlight

XR-E LED (Cree), 1x 1865O Li-Ion cell / 2x CR123 Lithium primaries, rear clicky on/off (forward contact sequence), 2 modes: maximum and dimmed (head twist selection), massive aluminum housing, parabolic reflector (coated aluminum)

Despite the massive differences between both lights, especially in terms of cost and the materials used, both use a simple parabolic reflector. The old-fashioned Varta offers limited focusing to eliminate the “hot spot” for close range illumination. It’s wide parabola allows for a lot of spill. The Fenix counters by with a sharp hot spot with superior range, based on a rather deep parabola with limited spill.

Summary

The current level of reflector development in general and automotive lighting has not yet fully been transported into the field of portable lighting. By using established optical free form components, flashlights of all cost and application field can be improved.
The paraboloid form can be upgraded with small effort to create perfect beamshapes. More complex parts, such as collimators and custom tailored combination optics can extend the range of possible light patterns and offer enhanced light control.