LED and Fresnel design and characterization Using Zemax optical design code

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Abstract – LEDs are more commonly being used in optical systems due to the advances in LED technology in power, efficiency, cost and wavelength output; especially white light LEDs. Fresnel lenses are also cost effective and advancements in aspheric Fresnel lens manufacturing have made these lenses effective optical elements. Various optical design codes allow for accurate modeling of these incoherent light sources and here we use Zemax optical design software. Zemax is becoming the most commonly used optical design software for its capabilities, technical support, and cost. In this paper we discuss two techniques for modeling RGB and white light LEDs and characterize each technique using a Fresnel lens imaging system. LEDs and Fresnel lenses are both cost effective and are being widely used in various optical systems both in industry and defense applications.

1. Introduction

High power LEDs are replacing most lighting applications due to the lumen output, size, and affordable cost. Therefore, modeling high power LEDs is important to predict performance applications such as the lumen output and the light distribution. Typically, these LEDs are used in a variety of arrays to achieve the desired lighting affect for commercial, industrial, or even personal applications. A representative is the Luxeon Rebel Cool-White LED which produces a minimum of 100 lumens at 350mA and up to 180 lumens at 700mA drive current[1]. A wide range of colors are offered from cool-white, warm-white, red, green, blue, and more. Proper heat sinking needs to be considered when using these high power LEDs even at the lower operation current levels. The heat is drawn from the circuit board, where the LED is soldered onto, and transferred to a typical aluminum housing heat sink or internal fans to keep the LEDs cool. The lower the LED temperature is kept, by managing the heat transfer, the more efficient and longer life it will have.

The light distribution is Lambertian, which means it is equally bright from any direction and is highly divergent even with the silican lens encapsulating the LED. Therefore, a refractive or diffractive lens is used to help collimate the light, but this collimation will not be perfect since the LED has length and width dimensions; or is not a point source. Small Fresnel lenses are best used for this purpose since they can be manufactured small and are cost effective. In this paper modeling of LEDs (high or low power) and the use of Fresnel lenses will be described. Modeling of the LEDs will primarily be discussed, and then we will briefly provide a Fresnel lens example. Fresnel lenses can be designed/modeled in sequential and non-sequential raytracing; where non-sequential allows for CAD imports as well as analyzing scattering and real detector outputs.

2. LED Modeling

The Luxeon Rebel LED will be used for the purpose of illustration and example throughout this paper so Figure 1 depicts two types of this LED and illustrates its composition.

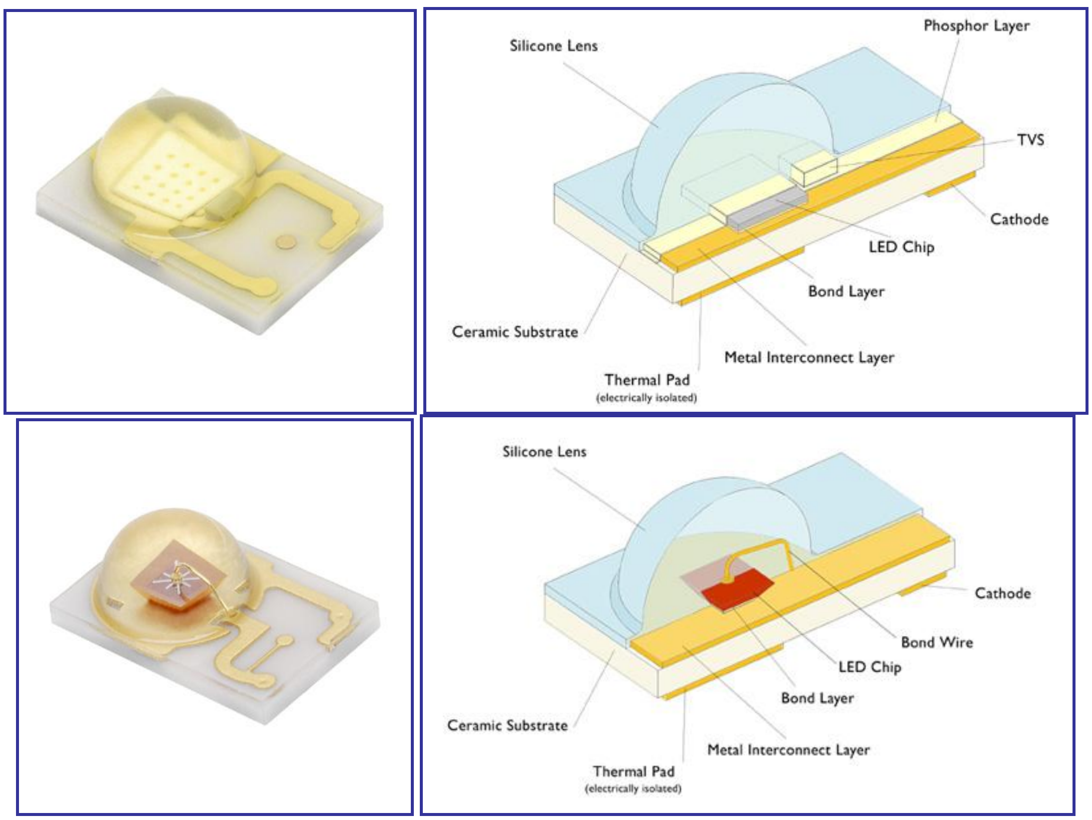

Figure 1: (Top) Drawings of Luxeon Rebel Cool-white LED, (Bottom) drawings of Luxeon Rebel AlInGaP LED[1].

Figure 1 gives images of the Luxeon Rebel LEDs. Some LED manufactures will provide CAD files for the LED models with the LED die dimensions that can then be imported into Zemax optical design code[2]. This is required in order to know the exact dimensions of the LED module as well as the LED die, which will define the LED light propagation and distribution on and before target. To be even more accurate the LED die bond lead can also be modeled, which typically run from the center of the die to the edge of the module. These LED die structures (bond wires or other components) will be imaged or alter the light distribution due to diffraction. An imported CAD file (STP or IGS) of the LED module has one issue, and that is they are usually one solid piece and in Zemax a material needs to be assigned to the imported CAD file. The CAD module includes the lens, which cannot be separated in Zemax. In order to assign the proper materials to each CAD module component they have to be separated. The module, the die, the bond lead (or any other die structures), and the lens need to be separate and a material assigned to each. The module is usually assigned to “absorb”, the die can be assigned to “mirror”, the lead is assigned to “absorb”, and the lens to silicon, silica or acrylic. Experimentation of the lens material may be required if the manufacture will not release that information. The LED die has length, width, and height dimensions therefore the Zemax Source Volume is the best source to use to properly model the die dimensions. The Cool White Rebel LED die has dimensions of 0.47mm x 0.47mm x 0.02mm. These dimensions are approximated from the CAD import and/or from observing the detector light distribution shown in a later section of this document.

There are two ways to break the LED CAD into components, one is to use a mechanical CAD software package, and the second is to use these dimensions from the imported CAD file and build a module in the Zemax non-sequential editor using rectangular volumes and the standard lens. The later is described here assuming that the reader is does not own a mechanical CAD software package. Also, using the built-in Zemax rectangular volumes and lenses allows Zemax to compute at a much faster rate. Each CAD import adds to the computation time for Zemax to trace and scatter rays off of each CAD import.

Figure 2: (Left) shows the CAD modeled import of the Luxeon Rebel AlInGaP LED and on the (Right) is the CAD modeled import of the Luxeon Rebel Cool-White LED.

Figure 2 demonstrates the Rebel AlInGaP LED with the bond wire (or lead) as compared to the Cool-White without the bond wire. Later it will be shown how the bond wire affects the light distribution.

The other option is to import the LED rayset provided by the manufacture into Zemax as a source file. A rayset is an accurate mapping of the LED distribution and lumen output experimentally by the manufacture and is provided in Zemax as well as other optical design code formats. If a rayset is used then the only purpose for the LED CAD import is for aesthetics, which may be important for presenting the model and/or for ensuring correct dimensions/position of the LED. Using a rayset is the more accurate way to model the LED, but not all manufactures provide rayset files.

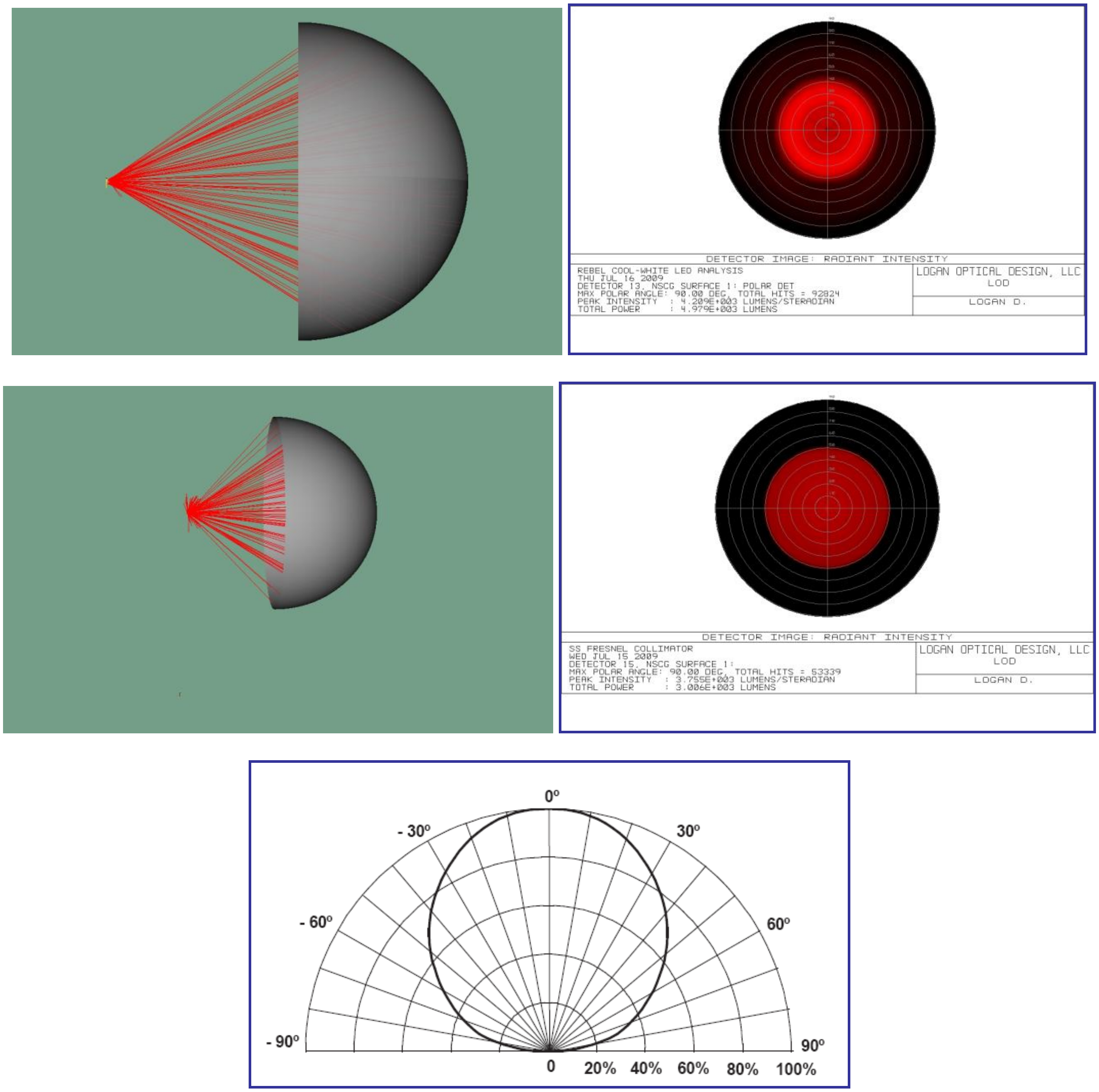

Figure 3: (Top) CAD model Rebel Cool-white polar layout and detector output to be compared with the (Middle) rayset polar layout and polar detector output. On the (Bottom) is the Luxeon polar output chart to compare the CAD model and rayset model[1].

Figure 3 shows how the rayset differs from a CAD model to a rayset. The polar plot for the rayset more closely matches the Luxeon polar chart, which is an indication that the rayset can be more accurate. The major cause of error is from not knowing exactly what the lens material is made of due manufacture proprietary reasons. The LED model is probably absorbent, but that is unknown as well. However, it will be shown in the next section how the detector intensity light distributions are fairly close to the rayset as well as the power and irradiance distributions. There are also other means of comparing your model with the manufacture specifications such as power output (in lumens), intensity profiles, and detector outputs as shown below in the next section.

3. Fresnel Lens Modeling and LED Collimation

The LEDs shown in the previous section have a divergent distribution even with the silicon micro-lens over the LED die. This light can become fairly collimated with the use of preferred small Fresnel lenses. Logan Optical Design (LOD) typically designs the Fresnel lens in the sequential (geometrical) portion of Zemax, and then imports that as a CAD file into the non-sequential portion of Zemax to be used with the non-imaging LEDs. The design of Fresnel lenses can spherical or aspheric. Most manufactures and optic houses have aspheric or can produce aspheric Fresnel lenses for the same cost as spherical lenses so it is best to vary the conic and/or the even or odd aspheric polynomial terms in Zemax to achieve the best collimating and efficiency performance. Usually only two or three polynomial terms are required with or without the conic in order to find the best optimization for eliminating spherical aberrations. This is normally only done on one surface of an acrylic Fresnel lens with the other surface being flat without any Fresnel rings. Also, it is important to design the Fresnel lens for only one wavelength and note that the bandwidth is especially small since diffraction principles are used to focus the light. In addition, attention has to be paid to the orientation of the Fresnel lens rings with respect to the LED for best performance or spacing of the LED to the Fresnel lens. The distance from the LED die to the rings of the Fresnel lens must match the focal length of the Fresnel lens. The reader must account for the thickness of the Fresnel lens and note that the distance from the die to the surface of the Fresnel rings is accurate, not from the center of the Fresnel lens as with single refractive elements.

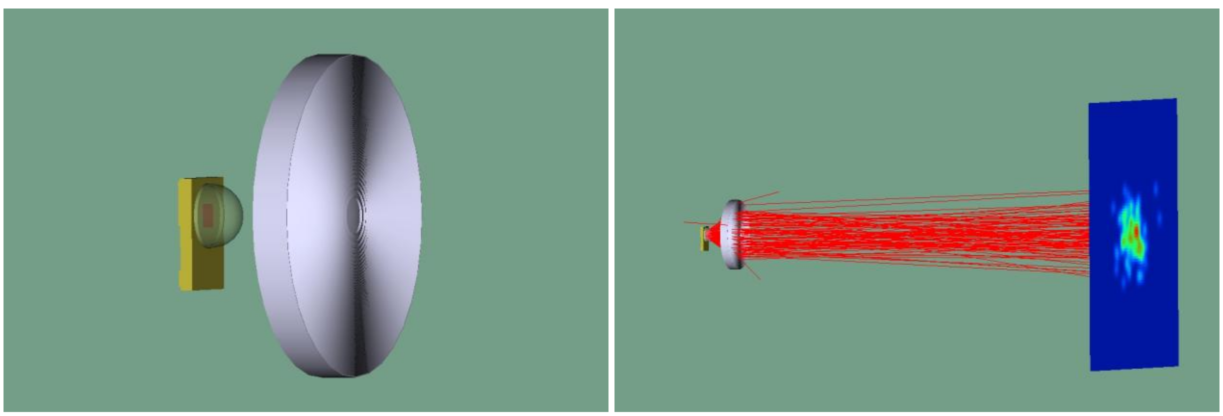

Figure 4: (Left) Fresnel lens and LED orientation, (Right) LED light distribution collimation using an acrylic Fresnel lens.

Figure 4 demonstrates how a small cost effective Fresnel lens will nicely collimate a high power LED. The number of rays used for analyzing LEDs, with or without the use of collimating Fresnel lenses, should be 100,000 or greater in order to achieve sufficient detector contrast. Note, however, that for sensitive applications the high power LED light will heat the Fresnel lens so one must account for expansion effects of the Fresnel rings; only for very sensitive applications.

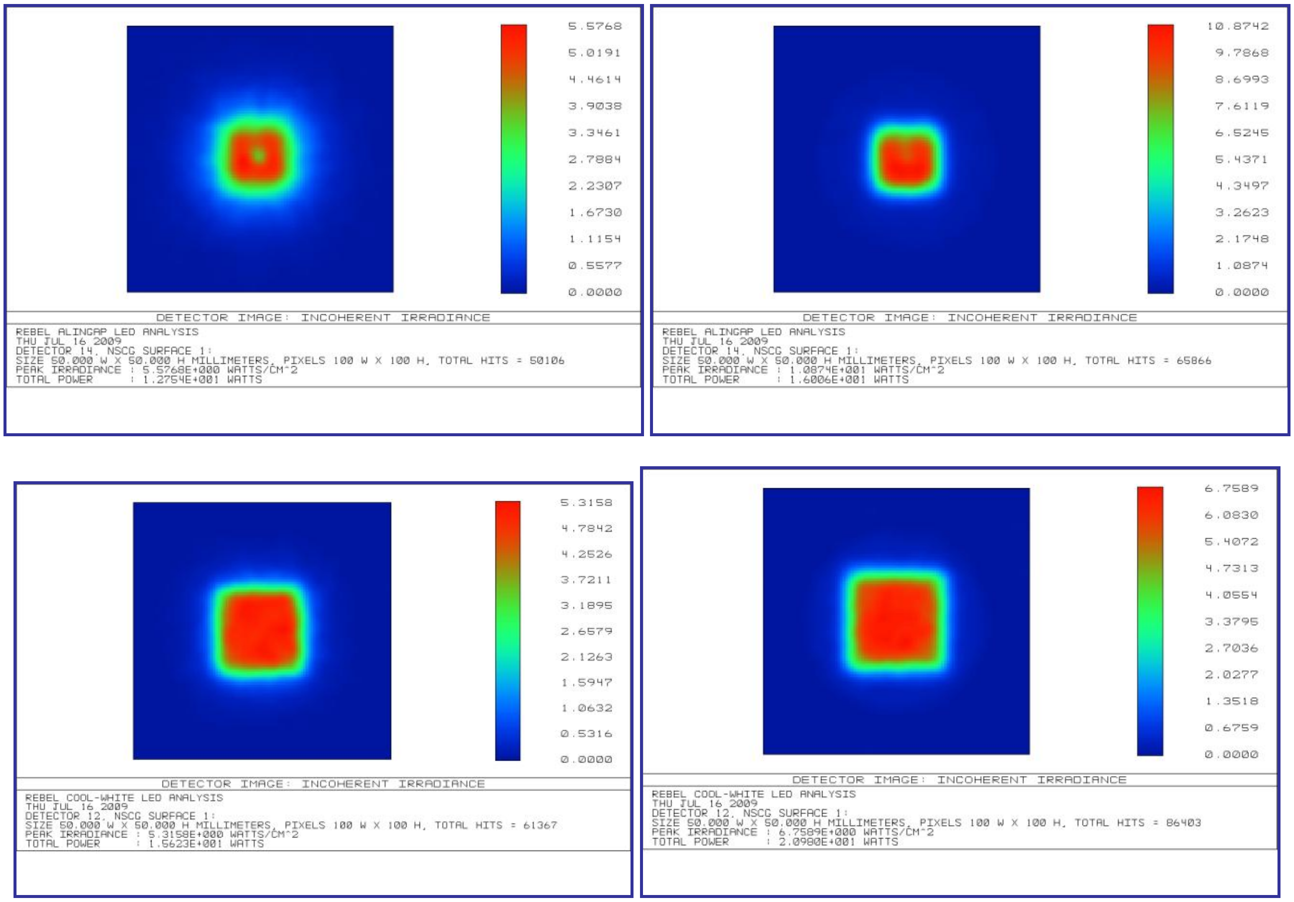

Figure 5: (Top) Left is the Cool-White rayset while on the left is the AlInGaP rayset detector patterns using the Fresnel lens. (Bottom) Left is the Cool-White CAD model while on the left is the AlInGaP CAD model detector patterns using the Fresnel lens.

Figure 5 shows a fairly accurate comparison between the rayset and CAD modeled LEDs. Again, the rayset (Top of Figure 5) are the most accurate representation of the LED since it was generated experimentally by the manufacture, but if the rayset is not available then more than likely building a CAD model of the LED and die (most important) will do and be quite accurate.

The prescription for the LED CAD model source and Fresnel lens are provided for the reader in Table 1.

Table 1: Zemax prescription of Source and Fresnel lens.

Source	**X Pos**	**Y Pos**	**Z Pos**	**X Tilt**	**Y Tilt**	**Z Tilt**	**Layout Rays**	**Analysis Rays**	**Power**
Source Volume	0	0	0.05	0	0	0	15-150	100,000	From Manufacture
Non-sequential									
Source	**X Pos**	**Y Pos**	**Z Pos**	**X Tilt**	**Y Tilt**	**Z Tilt**	**Layout Rays**	**Analysis Rays**	**Power**
Source File	0	0	-0.65	0	0	0	15-150	Auto From Imported File	Auto: From Manufacture
Non-sequential									
Surf Type	**Radius**	**Thickness**	**Glass**	**Semi-Diameter**	**Conic**	**2nd Order**	**4th Order**	**6th Order**	**8th Order**
Fresnel	2.941	1.5	Acrylic	6	-0.99947	0	5.2e-4	-2.8e-6	0
Sequential	**Vary**				**Vary**		**Vary**	**Vary**	

Source	**Wavenumber**	**Color**	**X Half width**	**Y Half width**	**Z Half width**
Source Volume	0, 1, 2, …	0, 1, 2, …	0.01	0	0
Non-sequential					
Source	**Wavenumber**	**Color**	**Randomize**	**Total Watts**	
Source File	0, 1, 2, …	0, 1, 2, …	1	Auto: From Manufacture	
Non-sequential					
Surf Type	**10th Order**	**12th Order**	**14th Order**	**16th Order**	
Fresnel	0	0	0	0	
Sequential					

Table 1 show the Source Volume, Source File and Fresnel lens prescription, which will help start the reader with modeling a LED and a Fresnel lens. The Source Volume and Source File are in non-sequential while the Fresnel lens is designed in the sequential editor, but then exported as an IGS file then imported into the non-sequential editor to be used with the modeled LED.

Some notes: one is the source files have a Z-distance associated with them. For the Source Volume this is to keep the rays from being trapped inside of the module and die, therefore, the rays from the Source Volume must start propagating just in front of the die. For the Source File that distance of where the source starts propagating may have to be adjusted in order to ensure the distance from the source to the Fresnel lens is correct. Also note that the Source File includes the LED lens in the rayset. The entire LED module, die and lens are encapsulated within the rayset. Finally, for the Source File one of the parameters is called Randomization; this must be set to 1 to enable the rays to start propagating in the right direction.

4. Conclusion

LEDs coupled with cost effective Fresnel lenses are becoming a very popular way of delivering high power light sources for just about every applications ranging from the medical industry, DoD, industrial lighting, to personal lighting systems. These new generation high power LEDs are estimated to last 50,000 hours at full drive current of 700mA[1]. Therefore, running at half the drive current it is possible that these high power LEDs will last over ten years! The Cool-white LED additionally provides "true white" color which provides optimal lighting for applications such as cosmetics/cosmetic dentistry and surgery. Having the ability to properly model these LEDs and Fresnel lenses to be used with the LEDs is a valuable tool to understand and predict the total lumens and light distributions.

References and Links

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[1] Philips Lumileds Lighting Company, www.philipslumileds.com, (2009).
[2] Zemax Development Corporation, www.zemax.com, (2009).