

# Optical Design and Analysis of LCD Backlight Units Using ASAP

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## Abstract

The optical simulation, analysis, and design of backlight units (BLU) of liquid crystal displays, using ASAP optical modeling software, are introduced in this article. Two major types of BLU, i.e. edge lighting and bottom lighting, and their respective optical components are reviewed. The concerns in optical design of those components, namely the light guide in edge lighting BLU and the diffusion and reflection sheets in the bottom lighting BLU, are discussed. A scattering pattern is usually screen printed under the light guide, on which smaller scattering dots are sparsely located near the light sources while larger scattering dots are more densely distributed away from the sources. A diffusion sheet can be a Lambertian surface or with more sophisticated bidirectional reflection distribution function. The cross section of a reflection sheet may look like a parabolic curve that can be optimized. The structure of ASAP consists of the pre-processor that creates models and specify optical properties, the processor that calculates optical interactions, and the post-processor that retrieves and manipulates data for more analyses. The general procedure of ASAP analyses and optimizations of both types of BLU is introduced. The ASAP scripting language is powerful enough in optimizing the shape and dimensions of the BLU optical components fore mentioned. Finally the results of a case study of the design analysis for equal irradiance in a bottom lighting BLU are given to depict how the ASAP scripting language is applied to obtain the optimal locations for lamps.

## 1 Introduction

Since liquid crystals are not light-emitting materials, light sources must be added in order to make images viewable on liquid crystal displays (LCD), which have different sizes and are widely used on television sets, computer monitors, cellular phones, personal digital assistants (PDA), etc. It is generally called "back light" because light sources are usually placed behind the panel of an LCD, hence the backlight unit (BLU) for the module containing the light sources. A BLU consists of light sources and other optical installations for reflection

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and/or refraction. There are two major types of light sources in BLU: the cold cathode fluorescent lamp (CCFL) typically used in large-size LCD, and the light emitting diode used in small-size LCD such as cellular phone's display. Although differences for the configurations and components exist in both types, the theory of optics for the whole BLU is quite similar.

The BLU can be classified into two categories in terms of the location of the light sources inside the module, i.e. edge lighting and bottom lighting [1,2]. An edge lighting BLU has the light source located on one edge of the module (Fig. 1), and a light guide plate is installed for light to travel from the source to the viewer. The light guide is unnecessary in a bottom lighting BLU in which the light sources are distributed behind the display screen for direct view (Fig. 2). The advantage of the light guide in edge lighting BLU is the relatively uniform luminance for the entire module. The existence of the light guide, however, would dramatically increase the module's weight. Therefore, the edge lighting BLU is more suitable in small-size LCD applications such as notebook computers, cellular phones, and PDA. On the other hand, without the light guide and hence the bulky weight, the bottom lighting BLU is more welcomed in large-size LCD. The shortcoming of the bottom lighting BLU originates from its advantage over the edge lighting BLU, though. As the light sources now are placed behind the display for direct view, the shape of the lamp configuration may be visible, which in turn causes non-homogenous luminance of the module. How to achieve high brightness and homogenous luminance has always been an important issue in the optical designs of both types of BLU.

In order to reduce the time to market, it is very effective by using simulation software to cut the costs in the design and development phase. In addition, engineers may gain the knowledge and skills required to design something correctly and quickly through the computer

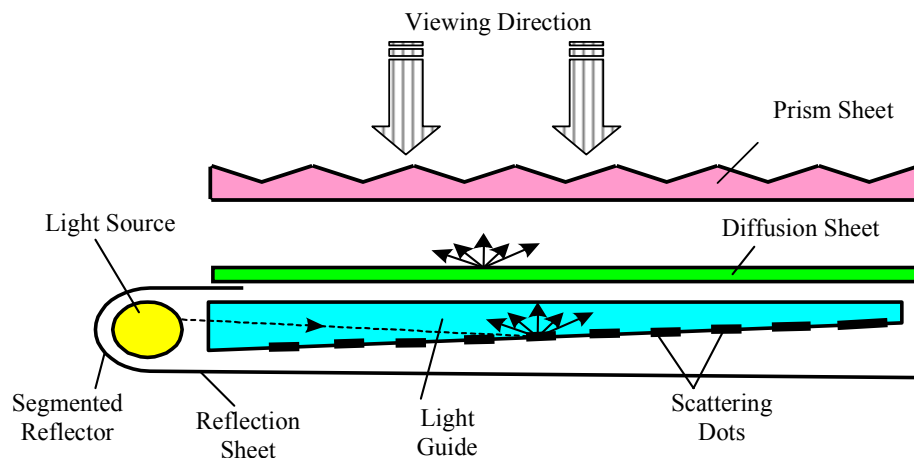


Fig. 1 Cross section of a schematic drawing of an edge lighting BLU.

aided engineering techniques. For the optical design of BLU, the Advanced Systems Analysis Program (ASAP™), developed and marketed by Breault Research Organization, Inc., is a powerful optical design and analysis software that includes capabilities for modeling physical optics, imaging, and illumination systems. The program's scripting language even offers the maximum flexibility for design optimization. This article not only introduces the optical design and analysis of edge lighting and bottom lighting BLU using ASAP, but also provides the authors' experience in performing design optimization through ASAP scripting language.

## **2 BLU Components**

Other than the light sources, the major optical components of an edge lighting BLU include segmented reflector, reflection sheet, light guide, diffusion sheet, and prism sheet (Fig. 1). For simplicity and clarity, thereafter we will view a BLU module from its cross section, and call the side far from the viewer "bottom" and the side near the viewer "top." The segmented reflector collects and projects lights into the light guide, while the reflection sheet reflects lights coming under the light guide back to the top in order to enhance the light efficiency. The light guide is a key component for edge lighting BLU as it directs lights from the edge to the top of the module. For more uniformly distributed lighting, scattering dots, which are formed by non light absorptive colorant with high reflection rate, are usually screen printed on the bottom side of the light guide. In general, the scattering dots distribute unevenly throughout the light guide. Fig. 3 shows that smaller scattering dots are sparsely printed on the portion of the light guide that is thicker and closer to the light sources, and bigger ones are more densely located on the thinner part of the light guide away from the light sources. In addition to the scattering pattern, some prismatic-shaped grooves [3] may be attached on the bottom side of the light guide, where lights are totally reflected to the top (Fig. 4). The diffusion sheet is capable of making uniform brightness by spreading the lights dispersed from the scattering dots, so that the viewer would not see the scattering pattern of the light guide. The prism sheet collects and reflects the uniformly diffused lights, and therefore enhances the screen brightness.

The configuration of a bottom lighting BLU is less complicated, compared to that of an edge lighting BLU. The core components of a bottom lighting BLU are reflection sheet, diffusion sheet, and prism sheet. The reflection sheet, located at the bottom of the module, reflects the lights coming from the light sources toward the BLU top in order to increase the display's brightness. The functions of the diffusion sheet and prism sheet are identical as those in an edge lighting BLU, i.e. diffusing and dispersing lights to improve brightness and uniformity. Since there is no light guide, the loss of lights due to transmission can be reduced, thus increasing the light efficiency. Therefore, given the equal amount of light sources, the brightness of a bottom lighting BLU is higher than that of an edge lighting BLU. There are usually two or more lamps in a bottom lighting BLU for more uniform brightness. The overall uniformity, however, may be poorer than that of an edge lighting BLU. The reason comes mostly from the significant difference in luminance between the lamp locations and the space flanked by the lamps. This excessive difference could be decreased by increasing the thickness of the BLU module. Nevertheless, the module must be as thin as possible because the consumer demands only drive LCD products thinner and lighter. As a result, the increase of the BLU module thickness is out of solution, and the only way to solve the dilemma is through optical design. The difference in luminance will simply amplify when the module becomes thinner, which makes the optical design of bottom lighting BLU more challenging for the purpose of uniform brightness.

### 3 The ASAP Optical Modeling Software

#### 3.1 Overview

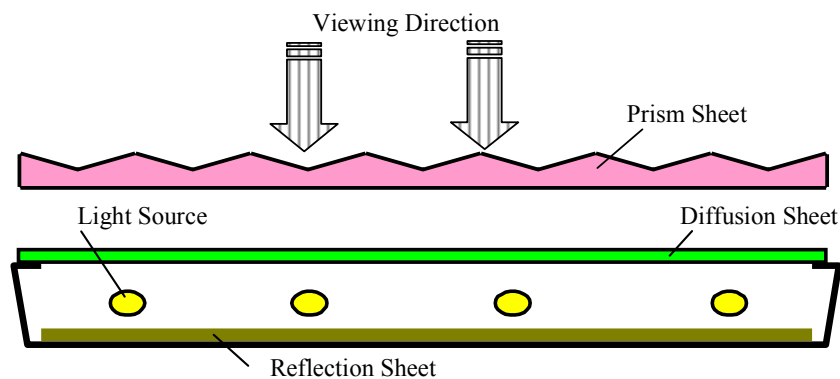


Fig. 2 Cross section of a schematic drawing of a bottom lighting BLU.

Fig. 5 shows a typical procedure of an ASAP simulation, which consists of three phases, i.e. pre-processing, processing, and post-processing. The pre-processing phase involves creating models of the optical system and light sources. The ray tracing program is the core solver in the processing phase. In the post-processing phase, various analyses can be performed.

In the pre-processor, users may build three-dimensional entity models of the optical system and sources, and assign appropriate optical properties to those entities. ASAP offers numerous commands in creating geometric entities [4]. Complicated geometries can be generated by commands such as **ROTATE**, **SHIFT**, and/or **BOUNDS** applying on various basic geometries. Other than all these tools required to model sources and geometries, system elements can be also imported into ASAP from other sources. Complex opto-mechanical systems can be imported from CAD programs via digital exchange format (DXF), or from a powerful built-in International Graphics Exchange Specification (IGES) translator. These created or imported elements then can be assigned optical properties. The **INTERFACE** command is used to assign optical properties on different objects, while the **MEDIA** command can be used to assign optical properties on a specific medium with non-zero thickness. Light sources in ASAP can be parallel sources, point sources, or extended sources which are often applied on BLU. The values of radiant flux (in watts) or luminous flux (in lumens) are needed to be input for light sources, in addition to their geometries.

In order to verify the accuracy of the models, it is necessary to use the graphical user interface (GUI) to check geometries and light sources, before proceeding to the analysis that follows. For the verification of geometries, special attentions should be paid to determine whether surfaces are connecting properly. Sometimes the **FACETS** command is required to make a geometry finer for verifying details. For the verification of light sources, the directions

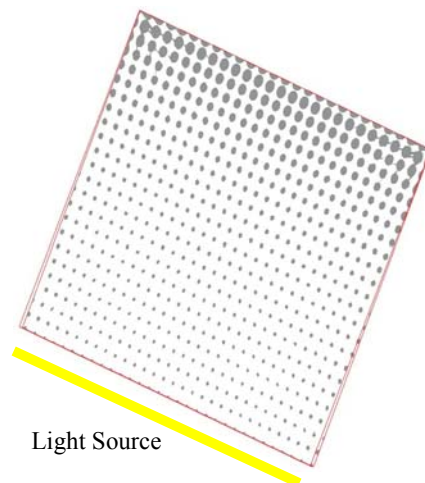


Fig. 3 Scattering dots on light guide.

of light beams and the luminous intensity of the sources have to be examined to ensure that they are conforming to the reality.

After the completion of geometric model creation, optical property assignment, and light source generation, the optical computation can be proceeded in the processing phase. The processor is able to calculate the interactions between light beams and other optical and/or opto-mechanical systems. The calculation is called the ray tracing. By completing the ray tracing, the simulation will enter the post-processing phase, where various optical information can be retrieved and viewed. For BLU, the typical information of interest include luminous flux, luminous intensity, illuminance, and luminance [5,6].

### 3.2 Optimization

Many simulation software offer GUI and interactive mode for users to easily construct geometrical models intuitively, which is the so-called "user friendliness." In ASAP, the Geometry Builder provides such an environment, where creating geometric models and light sources as well as assigning optical properties can be easily done in a spreadsheet. The subsequent ray tracing and post-processing can be performed through various pull-down menus. Nevertheless, this procedure may be awkward for someone who needs the "batch-mode" computation that usually appears in the process of design optimization.

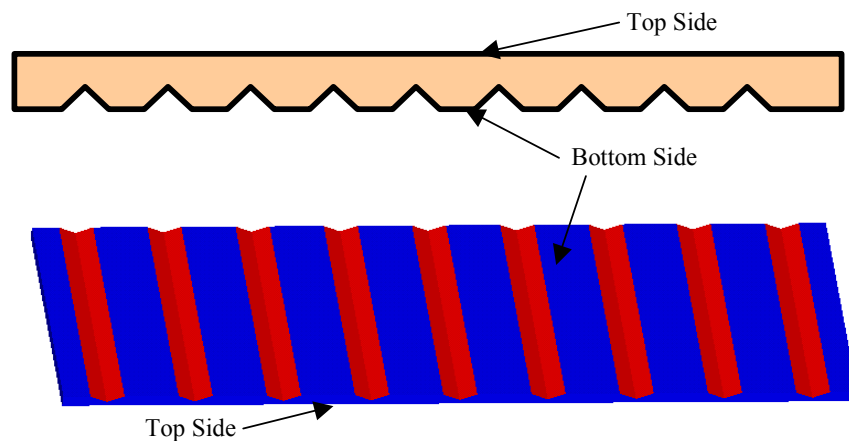


Fig. 4 Schematic drawing of the prismatic-shaped grooves under the light guide.

In general, a beginner may find difficulties in learning a software if it uses pre-defined programming languages to create models or even run the whole simulation. This kind of user interface, however, provides a convenient environment for design optimization. In the design of BLU, for instance, the luminance and its uniformity are functions of the lamp locations inside the module and the dimensions of other optical components. To achieve the optimal geometry, the parameters need to be varied throughout the design cycle. If the simulation is performed under the GUI and interactive mode, the model has to be modified manually and then computed every time it has been modified. This would be time-consuming and an inefficient way of simulation. For software with its own programming language, such as ASAP, parameters can be defined and passed between the main program and its subroutines or functions, while the objective function is calculated during the computation loops of the main program until the optimization is reached.

ASAP has a powerful scripting language that allows all ASAP commands to be typed in a text-editing window for sequential execution. Among the scripting language there are many macros which have similar syntax with those in high-level programming language such as C and FORTRAN [7,8]. This would allow users who are familiar with computer programming to maximize the software's capabilities.

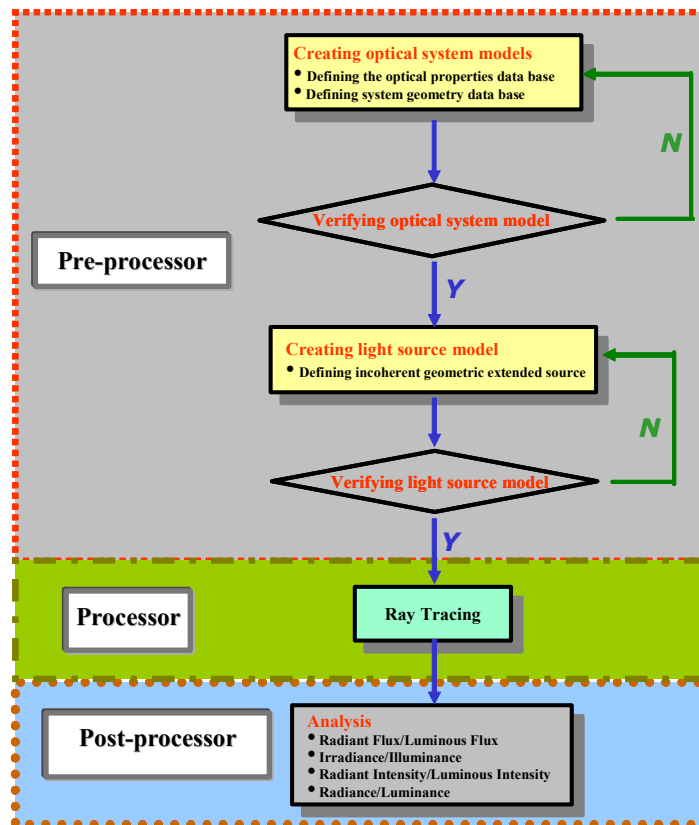


Fig. 5 Typical procedure of ASAP simulation.

## 4 Design and Analysis of BLU

### 4.1 Edge Lighting BLU

The key component of the edge lighting BLU is the light guide, which direct lights from the edge light sources to the top of BLU. The material for most light guides is acrylic plastic, which has the refractive index around 1.5 and the critical angle for total reflection being approximately  $42^\circ$ . The refractive index of acrylic plastic is higher than that of air, indicating there may have the total internal reflection within the light guide. This phenomenon is similar to that occurring in optic fibers. Yet the purpose of a light guide is directing lights out of it rather than keeping lights inside, as an optic fiber does. Therefore, shaped cuts like grooves would be fabricated on light guide so as to destroy the conditions for total internal reflection and to direct a maximum amount of lights toward the intended direction. The most important design parameters for such a groove are the angle and depth of the cuts, the transmission rate of lights, and the uniformity of light distribution. In ASAP, the groove model (Fig. 4) can be created by first rotating two planes (using **ROTATE** command) to form the slope surfaces, then bounding two end surfaces (using **BOUNDS** command) perpendicular to the slope surfaces. The optical property of the groove model (ASAP command line: **INTERFACE COATING BARE AIR ACRYLIC**) is identical to the other surfaces of the light guide.

To uniformly direct lights out of the light guide, scattering dots are typically screen printed under the light guide. The beauty of screen printing is that the patterns on screen can be readily changed. In practice, the scattering pattern may be first screen printed according to the initial design. Then a luminance meter is used to measure the light guide's luminance distribution, based on which the scattering pattern can be adjusted. The rule of thumb in adjusting the scattering pattern is that making scattering dots smaller and less denser in the region of high luminance, and vice versa. This is a guideline for design and simulation, where the principal parameters are the density and size of the scattering dots. In ASAP, the model of a scattering dot (see Fig. 3) can be created by bounding a circular tube and a plane (using **BOUNDS** command) to form a solid circle. For simplicity in assigning optical properties, a

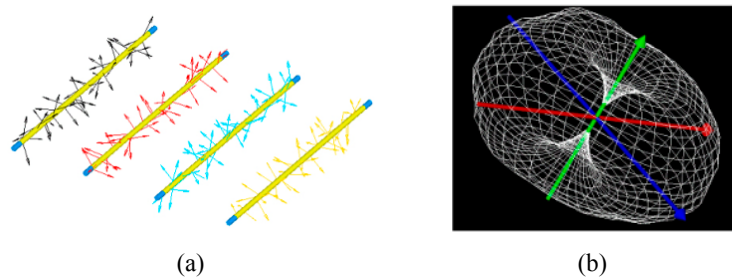


Fig. 6 ASAP plots of the light sources: (a) light beam plot; (b) radiant intensity of a lamp.



scattering dot can be treated as a Lambertian surface on which the luminance is constant in all directions. If some measured data are available, however, the more accurate bidirectional reflection distribution function (BRDF) can be employed in the computation. The optical properties on areas other than the scattering dots are same as those of acrylic plastic.

After the model generations and optical property assignments are finished, the model for light sources is to be created. ASAP offers many choices of source types, including emitting surfaces and volumes, grids, and Gaussian beams. Among them the extended source, a kind of emitting sources, is the most frequently used light source for BLU. The first step is creating the source geometry. Since cylindrical CCFL is usually used in BLU, the **TUBE** command is invoked to generate such a cylinder, which can be then designated as an object of emitters (ASAP command line: **EMIT OBJECT**) and assigned its value of luminous flux. The correctness of the light source can be immediately examined by checking the directions of light beams and/or the luminous intensity (ASAP command line: **PLOT RAYS**). Fig. 6 shows the plots of such examinations. The luminous intensity plot of Fig. 6(b) clearly illustrates the Lambertian surfaces of the lamp, which is defined as a Lambertian source. The accuracy of the source model will significantly affect the simulation results. To more accurately model a light source, the luminous intensity distribution of the source can be modified based on available experimental data. Such feature in ASAP is called Apodization.

#### 4.2 Bottom Lighting BLU

There are fewer optical components in bottom lighting BLU where the reflection sheet and diffusion sheet are major ones. The most important design parameters are the module thickness and the distances between light sources and the module's top surface. As the module is thinner and thus the distance between a lamp and the top surface is smaller, the contour of the lit lamp is more visible. This means the luminance difference is getting larger and hence the poorer uniformity in brightness. A quick fix could be a transparent acrylic sheet with scattering dots on it. The scattering pattern is designed to block lights from lamp locations, rather than uniformly reflecting lights as the ones in edge lighting BLU do. The scattering dots are denser on lamp locations while they are sparser between lamps. These measures will

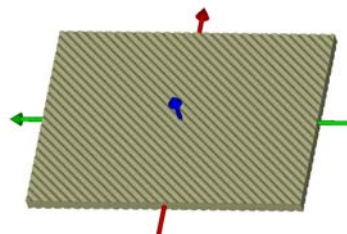


Fig. 7 ASAP model of a Moiré Lens diffuser.

reduce the luminance differences existing on lamp locations and the space in between, especially for thick BLU modules. The improvement is limited for thin modules, though. The luminance difference could be still too high to accept even scattering dots have been added. A diffusion sheet may effectively solve this problem.

For simplicity, the thickness of the diffusion sheet can be neglected in the simulation and replaced by a diffusive plane. The Lambertian surface is the simplest model. A more accurate model can be obtained by integrating data from experiments, such as measurements of the reflection and transmission of lights in the diffusion sheet, and deriving the BRDF. ASAP offers multiple choices for light scattering, including the Harvey bidirectional scattering distribution function (BSDF) and user-defined BSDF. If the effects of grooves, cuts, or Moiré patterns are to be examined, then the thickness of the diffusion sheet has to be considered. Fig. 7 shows an ASAP model of the Moiré Lens diffuser, in which the direction and size of the Moiré patterns are the critical design parameters. The geometry of this diffuser is created by the ASAP commands **TUBE**, **SHIFT**, **BOUNDS**, and **ROTATE**, plus logic operations that will determine which plane should be bounded with the tubes. The **MEDIA** command is used to assign the optical property, i.e. the refractive index, of acrylic plastic.

In addition to the diffusion sheet, a reflection sheet is also a feasible solution for the improvement of the luminance uniformity. The geometry of a reflection sheet can be designed to enhance the luminance on the space between lamp locations. Basically the cross section of a reflection sheet may look like a parabolic curve as shown in Fig. 8(a). A light source is placed at the focal point of the parabola, such that lights project parallel out of it. The cross-sectional shape of the reflection sheet can be either created by the ASAP command **EDGE** or defined by a mathematical equation of parabola containing user-specified design parameters. If the shape is generated through a derived equation of parabola, the command line **EDGE POINT** can be used to define the edge, from which surfaces can be created. The reflective index is the only optical property necessary for the reflection sheet. The simulation of the BLU enclosure, typically made of white plastic, is less complicated than that of the

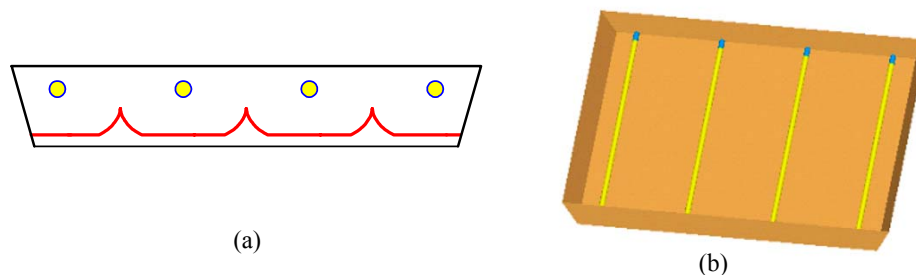


Fig. 8 ASAP plots of a bottom lighting BLU: (a) cross section showing the parabolic curve of the reflection sheet; (b) BLU enclosure as a five-surface open box.

diffusion sheet. Although there is thickness on the plastic, the ASAP model for the enclosure is simply an open box bounded by five surfaces with zero thickness as shown in Fig. 8(b). The reason for this setup is that the plastic material on those five surfaces is assumed opaque. Even if the plastic is translucent, the light transmission can be neglected by using the command keyword **BARE**. This assumption is valid as long as the simulation is focused on the lighting condition of the BLU's top surface.

We would like to clarify a confusion that many ASAP beginners may encounter. During the construction of the Moiré Lens diffuser (or other optical component), many temporary entities are created to bound for the component's shape. An entity, such as a surface, may or may not be an object for which the interaction with lights exists. An entity is not necessarily designated as an object in order to bound for a particular shape. In other words, the **BOUNDS** command is working for entities but not objects.

## 5 The Optimization of BLU

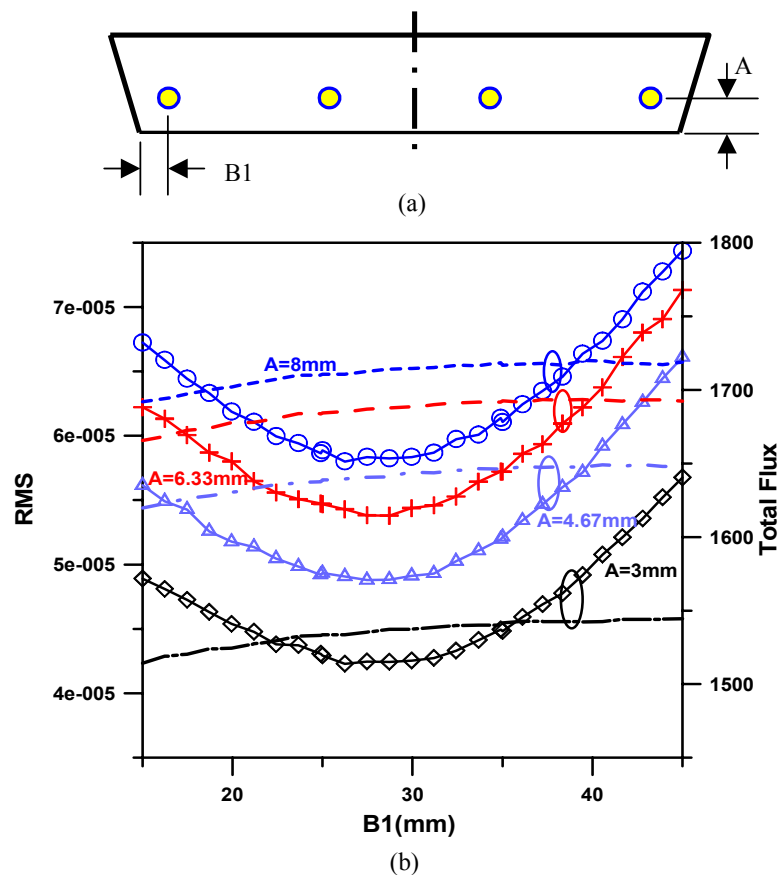


Fig. 9 (a) Locations of lamps in bottom lighting BLU; (b) distributions of RMS surface irradiance values (curves with symbols w. r. t. left ordinate) and total flux values (curves without symbols w. r. t. right ordinate).

The brightness and the luminance uniformity of BLU are functions of the geometrical factors of the entire module and all of its optical components. Those factors may include the enclosure dimensions, the number of lamps, distance between two lamps, distance between a lamp and bottom side of the enclosure, density and size of scattering dots, direction and size of the Moiré patterns, etc. All the factors need to be optimized to reach a best solution subject to given conditions. For example, given the dimensions of a particular BLU, the shapes and configurations of its optical components can be optimized. Should a given modular dimension or light source condition change, the optimal geometries of the optical components may change as well.

In ASAP, an objective function needs to be defined first in an optimization analysis. For BLU, this objective function could be the luminance and defined by geometrical parameters in the optical components. User-defined macros (defined by the **\$DO** command, see Appendix for example) can be used to iterate the computation and pass the variables. Post-processing is likely required to get the final answers from the optimization data. For instance, the computed luminance or irradiance will need to be calculated for its root mean square in order to find the uniformity. The **VALUE** command can be used for this purpose.

The Appendix is a partial program written in ASAP scripting language. Its main body

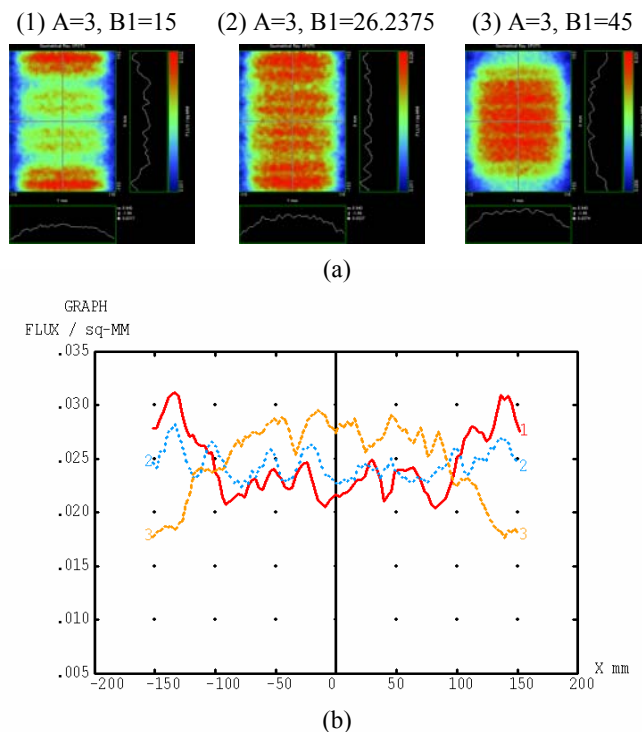


Fig. 10 A=3mm: (a) Irradiance distribution images for different B1 values; (b) irradiance distributions along BLU's center line.

includes two geometrical parameter iteration macros. One is **&NITER** that handles the outer do-loop and the other is **&F\_ITER** that takes care the inner do-loop. The six parameters given by **&NITER** determine the range and number of iterations. The structure of this program can be explained as follows. **&NITER** calls **&CALC** and passes four parameters into it. Then **&CALC** in turn calls **&GEOMETRY** and passes the first two parameters necessary for the geometry optimization into it for calculation. The latter two parameters passed are the identifiers for writing the output file.

Here we show some results from a case study to depict how to determine the optimal geometrical parameters for equal irradiance by using the methodology mentioned above, from which user-defined ASAP macros are applied to obtain the optimal locations for lamps in a bottom lighting BLU. This case study is to understand the influences of the distance between two lamps and the distance between a lamp and bottom side of the enclosure on the irradiance of a bottom lighting BLU by ASAP simulations. The optimal locations for lamps are determined without the presence of a reflection sheet and a diffusion sheet. Fig. 9 shows the distributions of the root mean square (RMS) values (see curves with symbols with respect to left vertical axis) of the bottom lighting BLU's surface irradiance and the values of the total flux (see curves without symbols with respect to right vertical axis), for different values of the "distance between the side lamp and side surface" B1 and the "distance between a lamp and bottom surface" A. It can be seen that better equal irradiances exist at smaller A values – distance between a lamp and bottom surface – and vice versa. The total flux increases as B1 – distance between the side lamp and side surface – being increased, namely the lamps get closer to each other. Fig. 10(a) shows the irradiance distribution images for different B1 values (B1=15mm, B1=26.2375mm, and B1=45mm) while A, the distance between a lamp and bottom surface, is fixed at 3mm. Fig. 10(b) shows the irradiance distributions along the module's center line, among which the case for B1=26.2375mm is the optimal.

## 6 Conclusions

We have introduced two major types of BLU, i.e. edge lighting and bottom lighting, which have different applications. The edge lighting BLU is more uniformly illuminated and mostly used on small-size LCD applications such as cellular phone displays. The bottom lighting BLU can be brighter and lighter, and is suitable for large-size LCD applications such as desktop computer monitors. It is worth mentioning that the demand for cellular phone BLU will increase as the cellular phones with color screen are more widely used. The ASAP optical modeling and simulation software has powerful and user-friendly features that help achieving the accuracy in the BLU design and analysis. Our case studies proved that the scripting language of ASAP gives users the capabilities of creating and simulating models parametrically. Its user-defined macros let an user write programs in modularized structures and

easily accomplish the optimization of the geometries and configurations of a bottom lighting BLU components. Similar principles can be applied on a edge lighting BLU to determine the optimal geometries of its optical components such as the light guide and diffusion sheet.

## Acknowledgements

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## Appendix

```
CALC {  
  &GEOMETRY #1 #2  
  .  
  .  
  .  
  DISPLAY  
  AVERAGE  
  WRITE A_#3_B_#4_AA_1  
  .  
  .  
  .  
  RAYS 0  
} !! END CALC!!
```

```

NITER {'OUTER LOOP, ITERATE FIRST PARAMETER'
$DO 1 (#3)
    &F_ITER ? #1 #2 #3 #4 #5 #6
} !! END NITER!!

```

```

F_ITER {'INNER LOOP, ITERATE FIRST PARAMETER'
$DO 1 (#7)
    {NIT1=(#4-1)
        $IF (NIT1) EQ 0 THEN
            VAR_PAR1=(#2)
        $ELSE
            VAR_PAR1=(#2)+((#3-#2)/(NIT1))*(#1-1)
        $ENDIF
        NIT2=(#7-1)
        $IF (NIT2) EQ 0 THEN
            VAR_PAR2=(#5)
        $ELSE
            VAR_PAR2=(#5)+((#6-#5)/(NIT2))*(?-1)
        $ENDIF
        &CALC (VAR_PAR1) (VAR_PAR2) #1 ?} !!
    } !! END F_ITER!!

```

```

&NITER 15 17 3 1 10 10    !!PARAMETERS EXPLAINED AS FOLLOWS

```

```

!!-----ITERATION PARAMETERS-----
!! VAR_PAR1=RANG1, VAR_PAR1=RANGE2, ITER NO. FOR VAR_PAR1,
!! VAR_PAR2=RANG1, VAR_PAR2=RANGE2, ITER NO. FOR VAR_PAR2
!!-----ITERATION PARAMETERS-----

```