DLP® Technology: Solving design challenges in next generation of automotive head-up display systems

White Paper

Literature Number: DLPA057A
December 2014–Revised November 2017

DLP® Technology: Solving design challenges in next generation of automotive head-up display systems

Texas Instruments (TI) has developed automotive grade technology for the next generation head-up display (HUD) for automobiles. Car OEMs desire true augmented reality (AR) HUD systems with very large field of view and virtual images created over the road that are bright with saturated colors. TI DLP® projection technology facilitates large fields of view at far virtual image distances with high brightness and color saturation, options to optimize mechanical packaging, and use of multiple types of solid state light sources for next generation HUD.

1 Introduction

TI DLP projection is a mature and widely used technology in numerous display applications including: hand-held projectors, conference rooms, and digital cinema theaters. DLP technology is well suited to meet the needs of advanced HUD systems wide field of view (WFOV) and long virtual image distances (VID). In this paper, we will discuss AR HUD display optics, source selections for a HUD using DLP technology (DLP HUD) designs, and the high dynamic range LED control system.

2 Augmented Reality HUD Display Optics

DLP automotive projection systems have characteristics that enable Wide Field of View (WFOV) in HUD systems, which are needed for next generation augmented reality displays. DLP technology has distinct advantages for design flexibility in the optics, mechanical volume management, and thermal management of sunlight for displays with wide FOV and distant virtual image positions.

The goal of a HUD optical system is to present the driver with a virtual image at a viewing distance typically at ~2 m. This virtual image may contain instrument cluster data such as speed, navigation, or other real time information to assist the driver. Given the nature of this information, a virtual image distance (VID) of 2 m is acceptable. An AR HUD display adds information related to events in drivers lane of traffic, and ideally in adjacent lanes as well; information such as off-ramp signals, turn directions, or driver safety information related to road hazards. By their very nature, AR HUDs require a longer virtual image distance (7.5 m to 20 m) and a wider field of view (10° to 15°). The benefit of increased virtual image distance allows the driver to view the road and the display without having to refocus their eyes between the displayed information and the scene of the road.

A DLP HUD optical system consists of either one or two curved mirrors, a diffuser screen and a picture generation unit (PGU). The PGU consists of the illumination source, the Digital Micromirror Device (DMD) plus drive electronics, and the optics required to image the DMD onto the diffuser screen. A typical system sketch is shown in Figure 1.

Current automobiles are limited in dashboard space due to the necessary structural beams, climate control ducts, and steering columns. These factors limit the size and shape of the space available to a HUD system. As seen in the HUD optical system sketch in Figure 1, a change in the vertical FOV can significantly shrink or expand the physical size and space required of the HUD mirrors due to the increase in light path area. Enlarging the FOV will require auto manufacturers to reroute structures to allow for additional open space behind the instrument cluster.

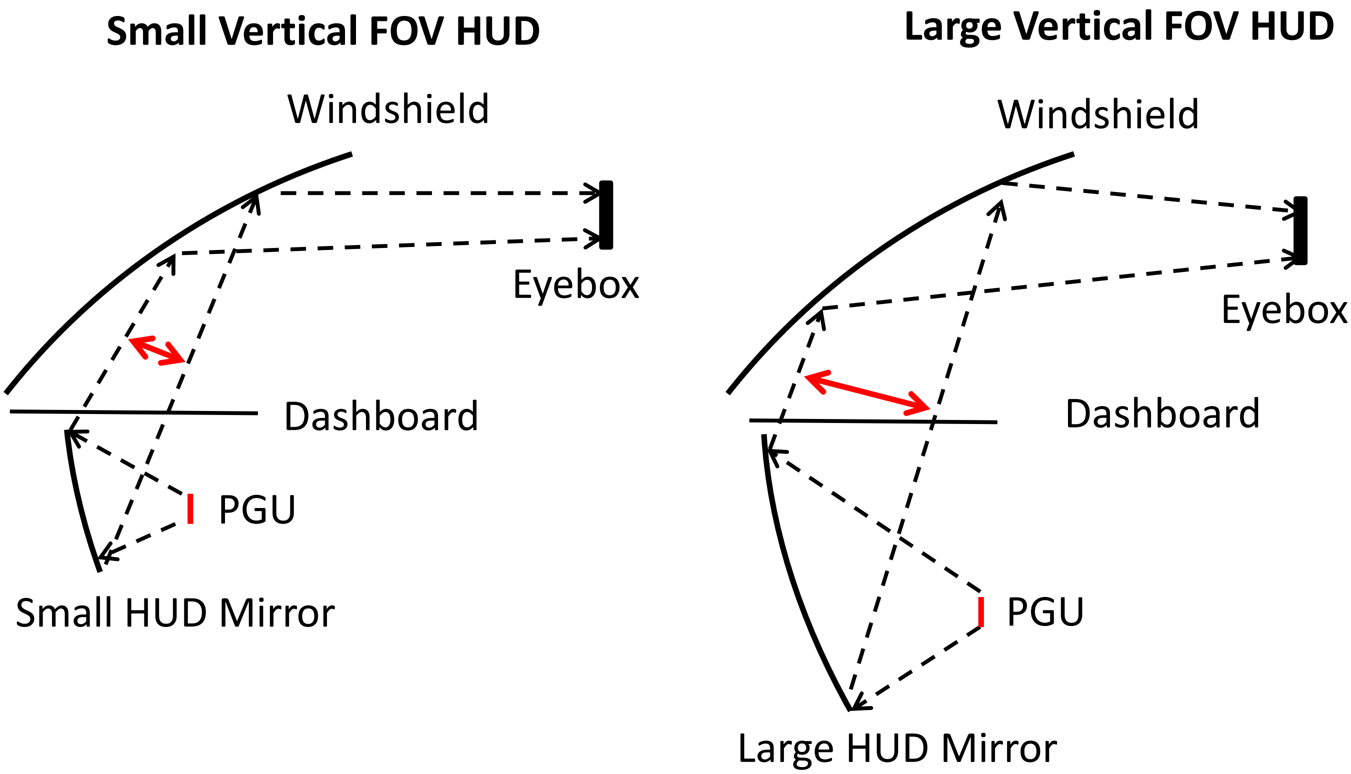

Figure 1. Dashboard Limited FOV

2.1 AR HUD Mirror Size

AR HUD mirrors are not significantly larger than those found in standard HUD counterparts assuming they both have the same FOV. The mirror width is expected to grow only ~17% as the virtual image distance ranges from 2.4 m to 10 m. If there is room to fit a standard HUD in a given dashboard volume then there should also be enough room to fit an AR HUD without significant modification. A simple geometric calculation can determine the required primary mirror size based on the virtual image distance and FOV. Figure 2 shows a plot of the mirror width increase verses virtual image distance for a 10° wide FOV HUD with an eyebox of 140 mm. The eyebox to primary HUD mirror distance used for the calculation is 1 m. The mirror width requirements increase minimally beyond a virtual image distance of approximately 10 m.

Figure 2. Mirror Horizontal Width for a 10° Wide FOV HUD vs Virtual Image Distance

2.2 Diffuser Screen for AR HUD

It is desirable for AR HUDs to produce up to 15,000 cd/m^2 of brightness so that the virtual image content can be seen when overlaid onto a bright sunlit scene. It is worth noting that no currently available automotive HUD achieves this brightness level. A DLP HUD can achieve this level of brightness through the efficient use of luminous flux enabled by an engineered diffuser screen.

In a HUD based on DLP technology, there is a diffuser located at the image plane of the HUD optics. This is in contrast to a HUD based on a direct-view technology (such as LCD), where the direct-view panel is located at the image plane. The diffuser screen is designed specifically to produce a limited scattering angle resulting in a brightness gain over a Lambertian scattering surface. This brightness gain and scattering profile are tunable by design to provide the proper eyebox shape, uniformity and brightness value required by the end customer. The brightness gain of the diffuser screen has a direct impact on the virtual image brightness. By adjusting these parameters the overall system efficiency can be maximized. The diffuser screen can also be optimized for size and position since it is not a fixed optical element. This enables the optics designer greater flexibility in the HUD optics layout to minimize the mechanical volume and conform to the space available in the dashboard.

2.3 Sunlight Thermal Load

Sunlight passing through the windshield within the FOV of the HUD will be focused and concentrated at the image plane. For AR systems, this effect is accentuated by the far virtual image distance and the wide FOV needed for AR. The diffuser screen in DLP HUD design is a passive element and can be made to be resilient to sunlight. The diffuser screen also functions to separate the PGU from direct sunlight. As a result, the DLP chip will be protected from a majority of this sunlight, due to the scattering at the diffusing screen and small aperture of the projection lens in the PGU further limiting the amount of sunlight to the DMD. The diffuser screen, being both a passive component and polarization insensitive, will not change significantly in performance under thermal loads.

2.4 Virtual Image Distance and Magnification

The FOV, virtual image distance, and magnification values for AR HUD systems are far larger than those in conventional small HUDs. The magnification ratio, which is the virtual image size compared to the diffuser image screen size, changes with virtual image distance. Figure 3 shows the magnification for a constant 73-mm wide diffuser screen image verses various virtual image distances for a 10° wide HUD FOV. All of the optics and mechanics remain the same but the magnification of the image will be 2× larger at 20 m than at 10 m.

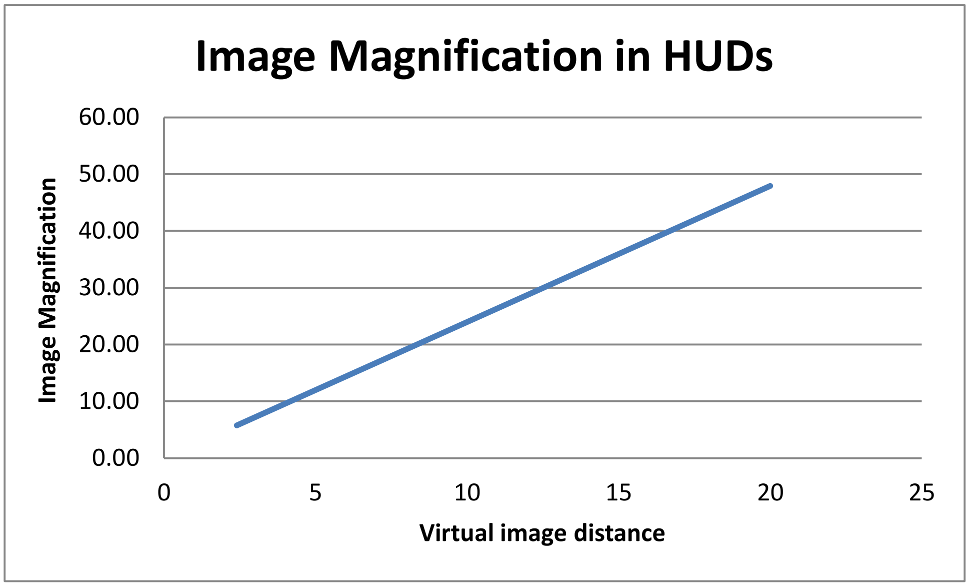

Figure 3. Image Magnification vs Image Distance

In the optics of an AR HUD, the virtual image distance can be controlled by a small translation of the diffuser screen relative to the HUD optics. For example, the virtual image may be shifted from 10 m to 20 m by a small adjustment of the screen position which could be less than 12 mm.

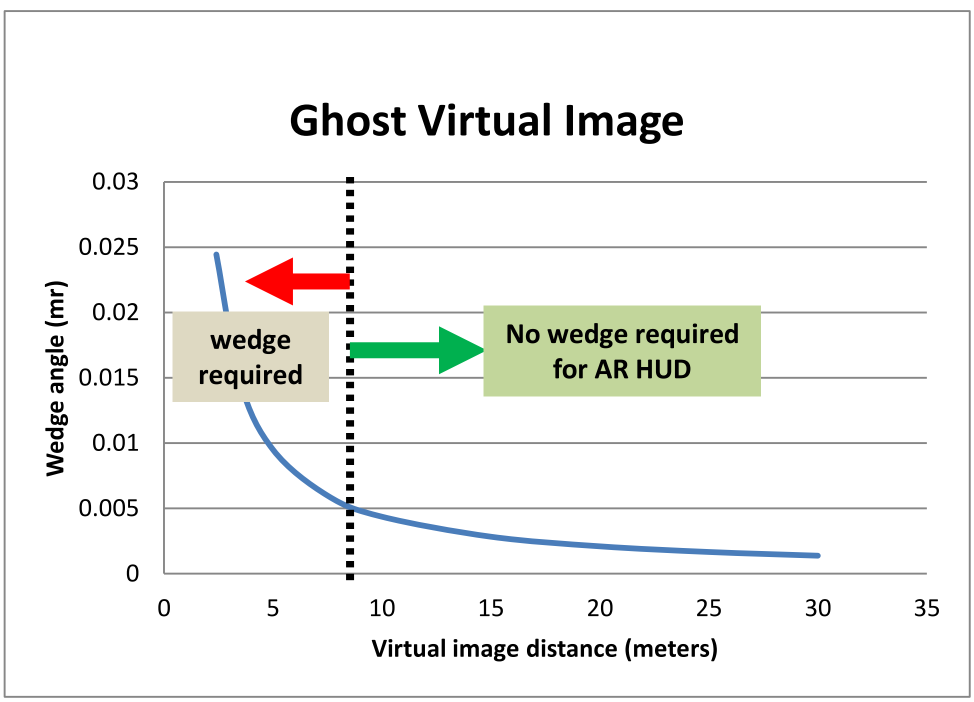

Figure 4. Windshield Wedge Angle

2.5 AR HUD and Wedged Windshield

HUD displays with a short virtual image distance require a wedged windshield to eliminate the double image created from front and back surface reflections of the windshield. The wedged windshield is no longer required for AR HUDS using long virtual image distances. The result is a meaningful cost savings to the OEM. Figure 4 shows a plot of the wedge angle in milliradians required to remove the double image caused by reflection from the front and back surfaces of the windshield. The plot is based on a flat windshield approximation, and assumes a 5-mm thick windshield of refractive index of 1.5, a downward look angle of 2°, and a 30° rake angle.

2.6 AR HUD Optics Summary

AR HUDs have many advantages over conventional HUDs in the ability to display more information in a more comfortable way to the driver. The increased size of the HUD mirrors between a conventional HUD and AR HUD are minimal. The added stress on the images due to increased level of sunlight concentration, increased brightness requirements, larger FOV, and longer virtual image distances can all be accommodated by a HUD based on a DLP technology.

3 Source Selection for DLP HUD

DLP technology is compatible with various types of illumination sources. These sources include lamps, LEDs, laser-/phosphor, and direct lasers. Source selection for the automotive environment must not only meet performance specifications, but also meet increased temperature and quality requirements.

Beyond automotive-unique requirements, the illumination source must be “optically matched” to the display device in order to couple the greatest amount of light in the most efficient manner. Etendue of the light source and display device is a method to evaluate this “optical matching”.

Etendue characterizes how “spread out” the light is in both area and angle. Etendue matching involves considering both the area of the devices (display device and light source) and the emission/admittance angles of the outgoing/incoming light. Figure 5 shows the layout of a simple optical system consisting of a source, a display device, and a single optical element coupling the source to the display device. Figure 5 also defines the etendue of both the source and the display device.

$$\text{Etendue}_{\text{system}} \approx \text{Etendue}_{\text{source}} \tag{1}$$

$$\text{Etendue} = \pi \cdot A_{proj} \cdot n^2 \sin^2 \theta \ (\text{mm}^2 \cdot \text{sr}) \tag{2}$$

$$\text{where } \eta = \text{refractive index} \tag{3}$$

$$\theta = \text{half angle} \tag{4}$$

$$A_{proj} = \text{projected area} \tag{5}$$

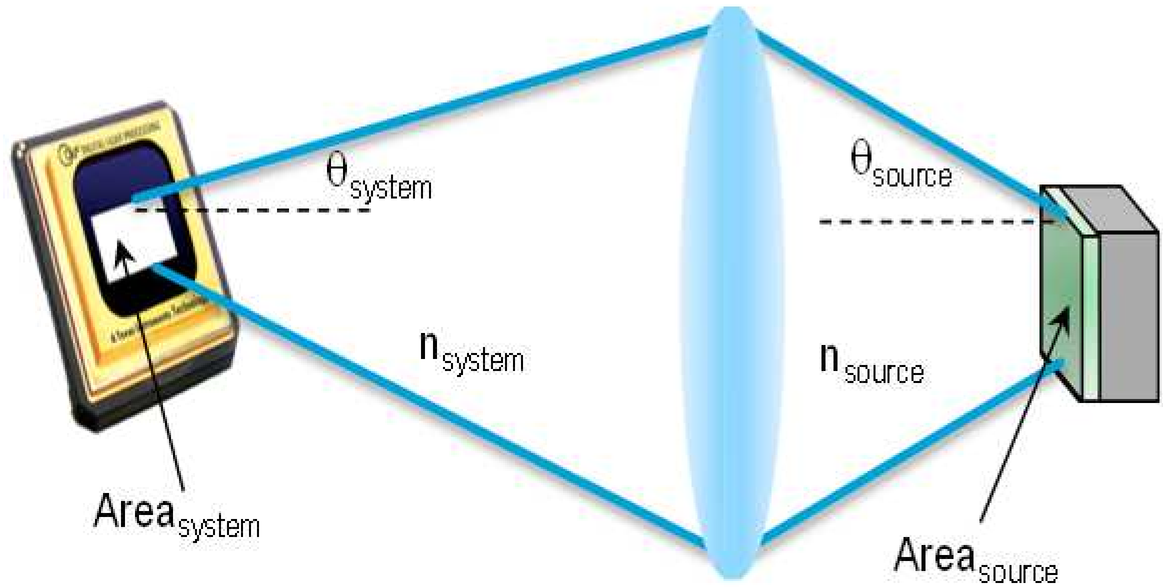

Figure 5. Conservation of Etendue

For a DLP projection system, the projected area of the DMD ranges from 11.1 mm^2 to 461.9 mm^2 depending on pixel size and resolution. The DMD can accept light with half angle (θ) of 12° without overlapping the input and output light cones. This large area range allows for the DMD to be matched to the appropriately sized illumination source. For a HUD system the typical projected area of the DMD device is about 22.2 mm^2 giving an etendue of 3.02 mm^2 sr.

3.1 LED Illumination Sources

LED illumination sources are offered in a large variety of sizes and colors. LEDs are being used in general lighting, TVs, and projection systems lending to economies of scale. LEDs are capable of illuminating extremely small projectors as well as bright projector models. LEDs are surface area emitters and range in size from about 0.5 mm^2 to around 12 mm^2. Etendue for a typical LED for projection would be approximately 1.15 mm^2 to 5.90 mm^2 sr.

LEDs are in full production and some have been automotive qualified. Speckle is not an issue and LEDs can operate at high junction temperature. Figure 6 shows a typical LED sequential illumination design.

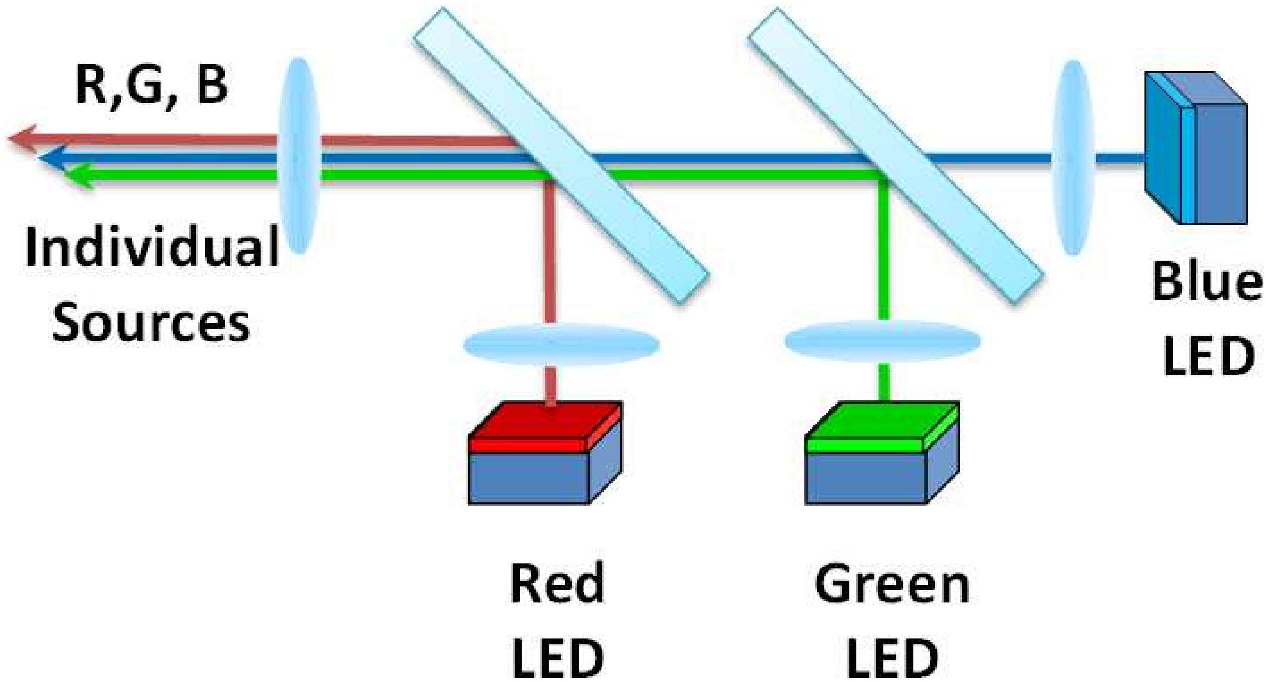

Figure 6. Typical LED Sequential Illumination

3.2 Laser-Phosphor Illumination Source

Laser-phosphor sources are increasingly being used in the design of projectors. The Casio XJ-A256 was one of the first projectors to use a spinning green phosphor wheel illuminated by a blue 448-nm multi-mode laser to produce green light with red and blue being supplied by LED sources. BMW and Audi have also announced use of laser-phosphor illumination sources in headlights.

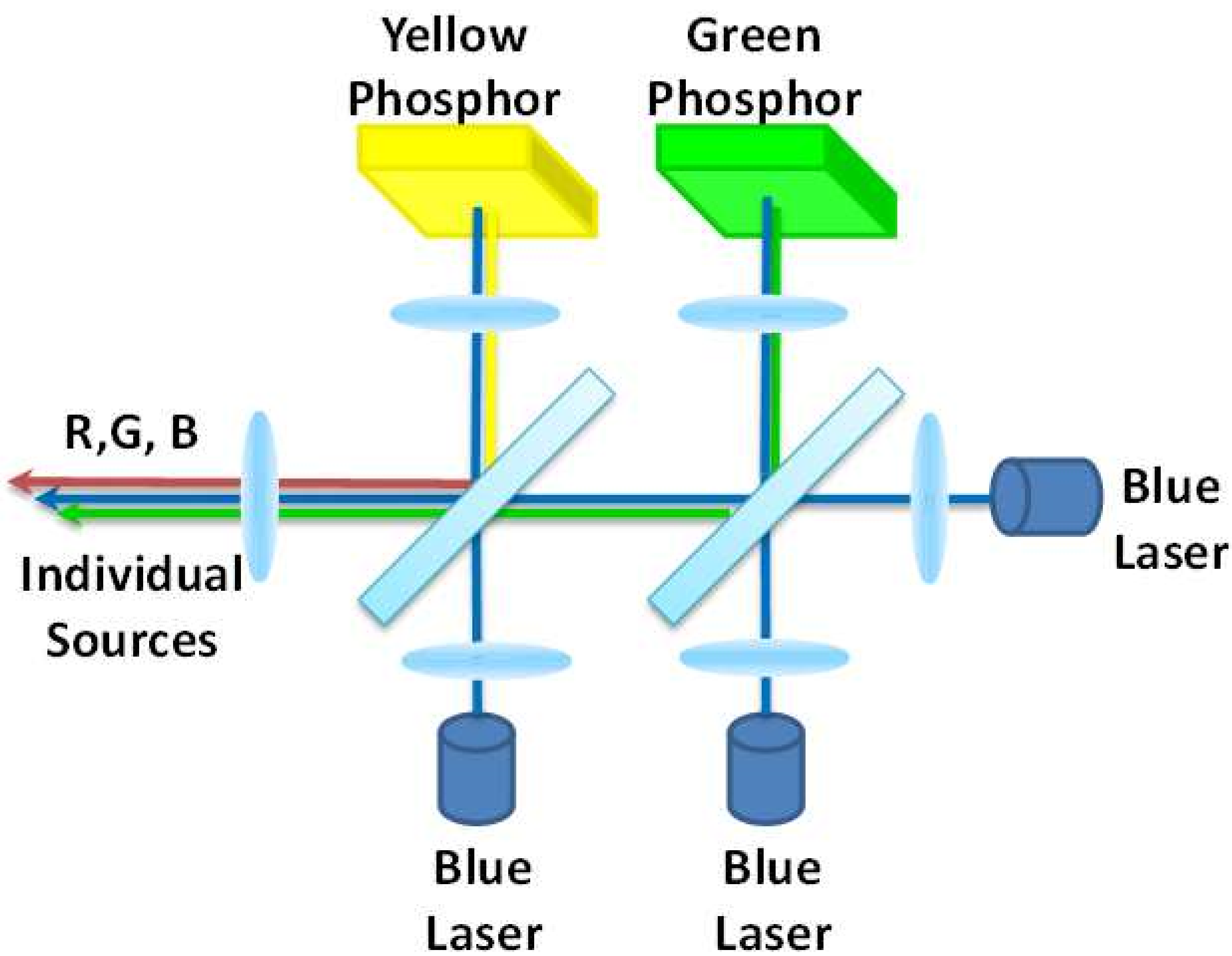

Figure 7. Laser-Phosphor Illumination

The laser, or a multiple laser array, can illuminate a phosphor with a very small spot of light making the area small, but the phosphor emission is lambertian and optics can collect only up to about angle (θ) of about 80°. The angle is similar to the LED source, but the small area illuminated by the laser can create a smaller etendue source. The etendue of a typical laser/phosphor emission is about 0.76 mm^2 to 3.05 mm^2 sr. Figure 7 shows a typical laser-phosphor sequential illumination design.

3.3 Direct RGB lLaser Illumination Sources

Laser illumination sources provide an advantage as an illumination source in that both the area and half angle are small. This provides for the lowest etendue and thus can potentially enable very small optical designs. A typical laser used in a projector design has an etendue of about 1.7×10^{-5} mm^2 sr before it is increased to deal with speckle. Projector system design looks similar to the LED illumination system design, but with laser sources replacing the LED sources. Digital Cinema projectors have been deployed with direct RGB lasers. The main barriers to widespread use of lasers in projection systems are operational temperature, cost, speckle control, regulatory compliance, and efficiency. These barriers have limited automotive qualification of direct RGB lasers.

In summary, DLP projection systems couple well to LED, laser-phosphor, or direct RGB laser systems. At present, LED sources are used in automotive systems today, laser-phosphor systems are used in consumer projectors with plans to move into automotive applications, and RGB direct lasers have a number of barriers to overcome before being viable in the automotive domain.

4 High Dynamic Range LED Control System

The HUD application requires a very high dynamic range to support a brightness of over 15000 cd/m^2 during day time operation, while also displaying an image at less than 3 cd/m^2 under very dark night time conditions. Additionally, this range must be implemented over a large ambient temperature range, (–40°C to 85°C) as required by automotive applications. The DLP3030-Q1 supports an operating temperature range of –40°C to 105°C to allow margin above the 85°C ambient temperature range requirement.

The DLP LED control system for HUD is described in application report DLPA043 found at www.ti.com. In this application report, only room temperature data was collected using the DLP HUD concept system. Since that time, the system has been further optimized yielding improved dynamic range and tighter white point control across temperature.

In Figure 8 the measured output brightness of the TI concept HUD system was measured at –40°C and 85°C ambient environments. The results show greater than 5000:1 dimming ratio in both cases. At –40°C, the minimum brightness was 2.95 cd/m^2 and a maximum brightness was over 18,000 cd/m^2. At 85°C, the minimum brightness was 2.73 cd/m^2 and a maximum brightness was over 15,000 cd/m^2. These results show the capability to achieve the necessary dynamic range under full automotive use conditions.

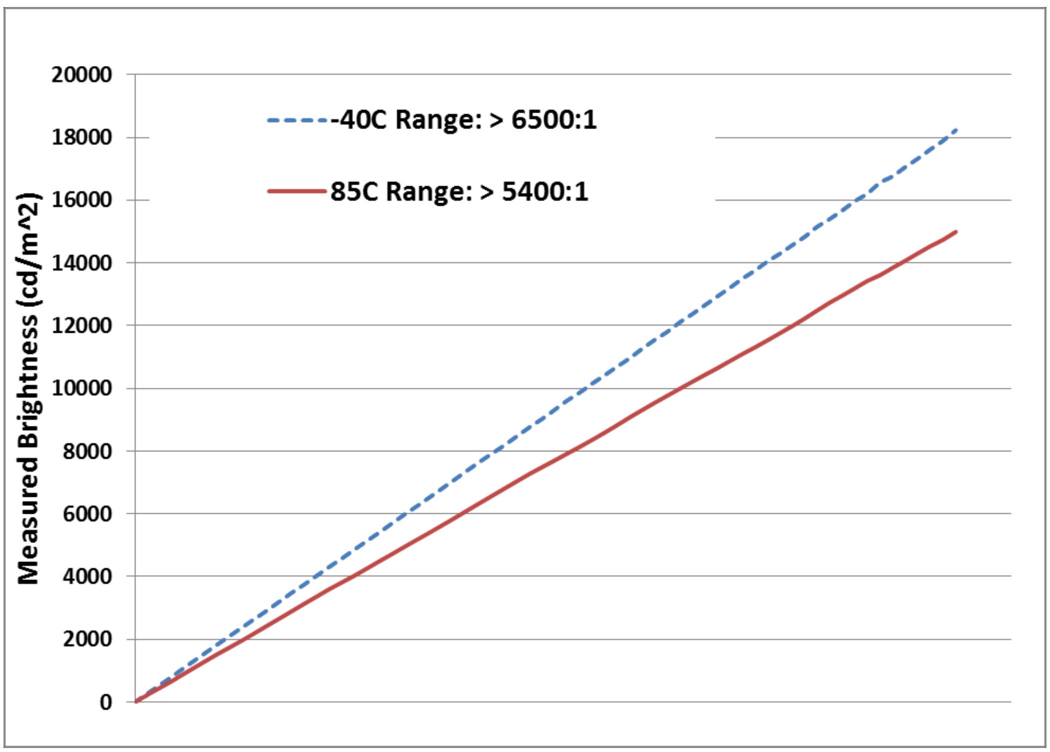

Figure 8. Measured Light Output for DLP HUD

In addition to achieving a wide dynamic range, the white point must be maintained. For the implementation in the TI concept system, D65 was chosen for the targeted white point, which is a standard used in most High Definition Televisions (HDTV). This white point has a target chromaticity value of x = 0.313 and y = 0.329. Figure 9 shows measured chromaticity data across the dynamic range is tightly held near the targeted white point. The total amount of variation from the targeted chromaticity point is less than ±0.005 across the entire dynamic and at both operating points of –40°C and 85°C ambient.

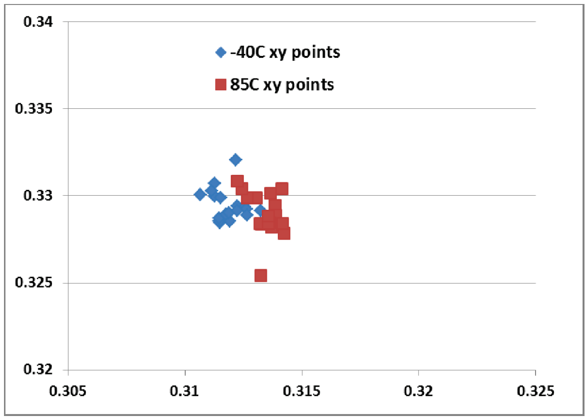

Figure 9. Measured White Point Over Dynamic Range

In summary, the LED driver control system implemented in the DLP HUD concept demonstrates necessary dynamic range and white point control while operating under the automotive operating conditions of –40°C and 85°C ambient environments.

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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265