DLP® Technology: Next generation augmented reality head-up display

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Abstract: Car OEMs desire to implement Augmented Reality (AR) Head-up displays (HUDs) with large display areas and long virtual image distance making it possible to display HMI designs that minimize driver distraction and increase situational awareness by incorporating advanced driver assistance system (ADAS) information. However, using conventional optics to create large HUD display images often results in very large systems that are difficult to integrate into the limited space that's available behind the instrument cluster. New technologies are now being developed that utilize advances in the areas of holographic films and waveguides. These new technologies have the potential to dramatically reduce the mechanical volume of the entire HUD system, while also enabling a very large display area with long virtual image distances. These new technologies, when combined with light sources that have narrow bandwidth (Laser), have the ability to enable completely new and enhanced driving experiences. DLP technology has already been proven to work very well with laser light sources for many consumer display applications in a variety of markets. This paper will provide a market overview of laser technology used in display applications that are currently available today, and will also cover the prospect of using laser illumination for automotive applications. It will also explain how laser illumination can be combined with DLP technology to optimize performance with measured and model data for contrast, electrical and optical efficiency, color saturation, and optical size reduction for both the HUD optics and DLP projection optics. This paper will illustrate different methods for combining DLP laser based projection systems with new technologies such as holographic films and waveguides that provide a path for very small AR HUD systems. Finally, a summary of market trends will be provided.

Keywords: Head-Up Display; HUD; Laser; DLP; Waveguide; Holographic Film, Augmented Reality

1 New possibilities with laser illumination [1]

Recent advancements in laser diode technology have inspired new interest in utilizing it as an illumination source for many new display and non-display applications. Higher electrical efficiency and improved optical output power for both visible and non-visible varieties offer new possibilities that can be of great benefit to multiple market segments – including automotive. With blue being the most mature (presumably due to its prolific adoption in blue-ray players), several display products now combine them with phosphor technology to create very bright and efficient, full color systems. The automotive industry has also appreciated recent advancements from laser diode technology for exciting new applications such as Lidar and dynamic headlight systems – both of which rely on the specific capabilities that only laser illumination can offer[1][2]. While laser diodes offer a lot of advantages to a variety of broad applications and have already gained significant credibility as reliable light sources, the technology still has some room for improvement before it can provide stable operation and fully meet the temperature demands of the automotive environment – particularly across the entire visible spectrum (especially red and green)[3]. Like most new technology advancements, it may simply be a matter of time before capabilities improve enough to be viable to support new applications in the harsh automotive environment.

One area of growing interest in the automotive space is in regard to AR HUD – specifically how to make the image brighter, have images that are farther away over the road, and provide fields of view that expand across the entire roadway. There are many new opportunities for new HUD designs to provide more information where the driver is already looking – out over the road as opposed to the area over the hood. Traditional HUD optical systems result in much larger mechanical volume to accomplish these features – regardless of display technology. However, by utilizing the capabilities of laser based projection systems in combination with other exciting new optical technologies, these mechanical size barriers can be overcome.

2 Benefits of laser illumination

While some of the properties of laser illumination are obvious and well understood by even those that are not technically minded, it is worth explicitly describing the key benefits that laser illumination offers. First, lasers offer the ability to provide illumination that is of a single wavelength (that is, monochromatic). This is important for some of the new technologies that will be discussed later. Second, lasers emit light from a very small source with relatively small expansion – allowing the light to remain compact over larger distances. Typical point source emitters send light into all directions or in the case of popular LED devices, light is emitted into a complete hemisphere, which results in larger collection optics. Third, lasers have a very high electrical to optical conversion efficiency. Based on recent modeling and analysis by Texas Instruments of laser illumination combined with DLP technology, lasers have the potential to significantly lower the electrical power required to achieve the same luminous flux as a system based on LEDs[4]. This increased efficiency is most appreciated by systems that have very small display panels (small etendue). This increased efficiency also enables smaller cooling configurations since more energy is converted to light as opposed to heat. For small compact display systems, this can provide a significant advantage to the overall system design and minimize the overall size of the entire system. It should be noted, however, that lasers have a maximum junction temperature of around 40-55°C to maintain stable operation[5][6]. For applications near room temperature (20-30°C), this is not much of a concern, and in fact may even enable designs without fans – but for automotive applications, this would likely require some creative thermal design. Lastly, in addition to being monochromatic, many lasers also have an inherent polarization bias. While polarization is important for some architectures and display technologies, it is not always a required feature nor always desirable. In fact, for display applications where lasers are used as illumination for some form of display device, using perfect, polarized, coherent illumination causes other non-preferable image anomalies. These image anomalies typically detract from the quality of the image being produced. One particular image anomaly of interest is that of speckle – an interference pattern that occurs from the interaction of the coherent wavefronts from the laser illumination, the surface that the illumination is reflecting from, and user's eye. Speckle is difficult to completely eliminate, but can often be reduced using various techniques. While lasers may not necessarily replace LEDs for all applications, their unique features will enable new architectures for both automotive and non-automotive applications.

(1) DLP is a registered trademark of Texas Instruments.

3 Benefits of laser illumination with DLP Technology

While DLP technology has many advantages for a variety of display and non-display applications, one of the more fundamental advantages of the technology is that it is light source agnostic. Since DLP technology is a reflective technology (each pixel being a mirror), multiple light sources of almost any type or wavelength may be used to illuminate the device. As a result, a wide variety of applications have been enabled by DLP technology and its versatility. Although DLP technology has enabled some of the most efficient and compact systems available on the market today, there is now additional opportunity for even more compact systems with the use of laser illumination sources. With DLP technology being reflective, lasers can be "dirty" in that they don't have to be polarized or uniform in their emission profile. This not only helps to reduce image artifacts (like speckle that was previously mentioned), but may also enable lower cost lasers and more flexibility with the design of the overall optical system. For example, this allows the use of multimode lasers with better thermal stability and reliability, without the need to preserve polarization.

Recent advancements in laser diode technology now enable new possibilities for illumination designs that couple perfectly with DLP devices from an etendue perspective and simultaneously offer very compact form factors. Most Digital Micromirror Devices (DMD) have very small active array sizes which often constrains the illumination architecture, requiring designs that utilize very small emission sources. Typically, most emission sources (arc lamps or LEDs for example) emit light into a full hemisphere, resulting in very large emission angles. Due to the principles of etendue (the optical invariant that states that the product of area and solid angle at any given location within an optical system must be preserved), careful design is required to maximize the coupling efficiency of those light sources onto the DMD active array area. The etendue for designs that utilize DLP technology is established by the area of the DMD's active array and the tilt angle of the DMD array mirrors. Thus, the illumination design must be optically "matched" so as to maximize the amount of energy that can be adequately collected and imaged onto the DMD array. Since the tilt angle of the DMD mirrors is fixed for a given device, the maximum etendue is the product of that angle and the area of the device's active array. For illumination sources such as LEDs that emit energy into large angles, larger collections optics are required to capture this light. Thus, larger etendue light sources limit the absolute minimum size that a given design might achieve.

Since lasers have a small emission area as well as very small emission angles, it is possible to take advantage of the very small etendue that exists with lasers and couple that illumination energy very efficiently with DMDs – enabling very compact systems. Multiple lasers can even be coupled together while still preserving small etendue. Lasers also enable the use of smaller cone angles while maintaining high coupling efficiency, which can result in significant size reduction. Figure 1 simplistically illustrates the definition of an optical system's f/# as being the ratio between the diameter of a system's exit pupil and the working focal length of the system.

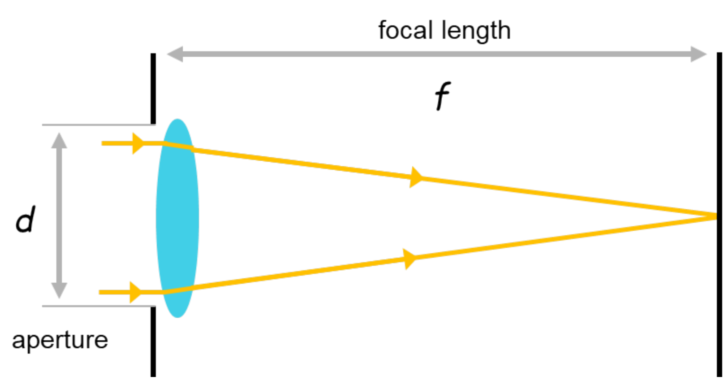

Figure 1. Definition of f/# (= f / d)

As described above, illumination sources such as LEDs emit light into a very broad angular space. This results in the need for a very small f/# - typically f/1 or faster ("faster" meaning faster expansion over a short distance – ie larger angle), and is required to preserve high collection efficiency of the illumination energy. For laser illumination, however, these high angles are not required – and efficient coupling of the light energy can be achieved with larger f/#'s (smaller cone angles). As a result, the overall size of the optical system can be reduced by 30% or even more. Figure 2 illustrates the size differences between various common f/#'s for typical DLP designs for both LED and laser illumination options.

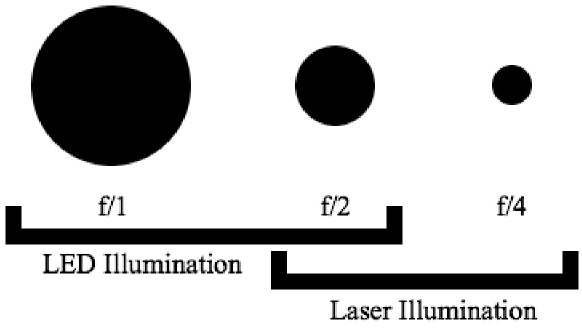

Figure 2. Illumination size comparison

Another advantage of smaller cone sizes (specific to DLP technology) is that contrast can be enhanced. For designs based on DLP technology, light enters the DMD at some incident angle and is then reflected into or away from the projection optics. As described earlier and illustrated for clarification in Figure 3, in order to achieve maximum brightness (that is, maximizing etendue), the illumination cone size that is incident to the DMD is often matched to the tilt angle of the digital micromirror device being used.

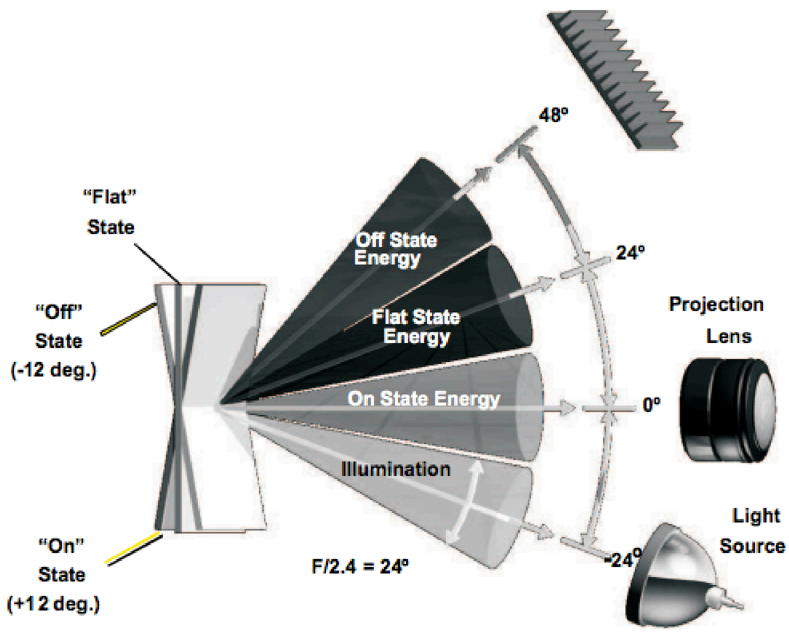

Figure 3. Simplified optical function of 12° DMD

Increasing the f/# (smaller cone size) reduces scattered light and improves contrast. Figure 4 illustrates the potential increase in contrast as a function of increased f/#.

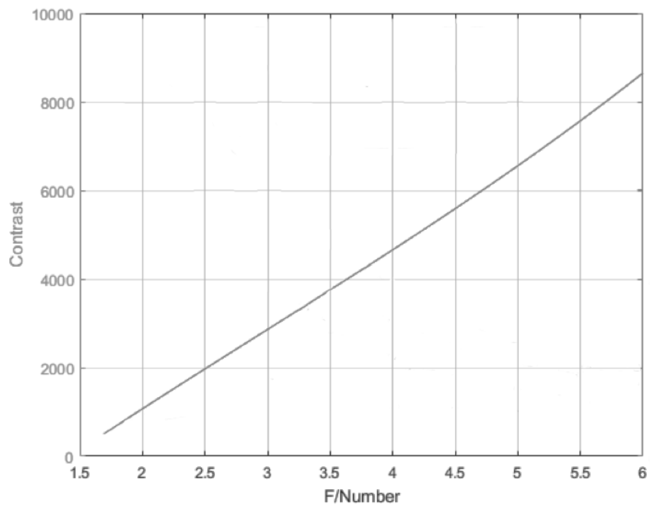

Figure 4. System contrast vs f/#

Laser illumination offers the ability to provide more illumination energy within smaller incident cones - which can actually enhance system contrast performance while also preserving optical coupling efficiency (etendue). System simplicity, improved efficiency, smaller form factors, and improved contrast are just a few examples of how lasers are a perfect match for DLP technology.

4 DLP laser based projection and new optical technologies: breakthrough for AR HUD systems

HUD systems are becoming more common and have been available in certain vehicles for decades. But, many current implementations have a limited field of view of about 5° with the virtual image distance often placed just over the hood, about 2.5m in front of the driver. This approach has been effective to date, with the expectation being that the HUD is only required to essentially duplicate information already available in the vehicle's cluster instruments (speed, rpm, etc) – but place the information closer to the direct line of sight for the driver while watching the road. As Advanced Driver-Assist Systems (ADAS) solutions have become more common, there is opportunity to provide additional information to the driver beyond fundamental data such as speed and engine performance. With recent advancements in sensing technologies and associated processing power, technologies in the vehicle now provide a much greater sense of awareness to the driver while on the road – during both day and night conditions. If these new capabilities were to be combined with AR HUD technology, much of this information could then be provided to the driver in a way that does not require the driver to shift their gaze away from the road ahead. Because of this, there is new opportunity for the head-up display to evolve beyond the traditional capabilities.

New head-up display designs have recently become available on the market that provide new capabilities such as wider fields of view and enhanced information for the driver – but are still far away from the ultimate goals desired by vehicle manufacturers. There is a desire to extend the field of view across the entire width of the road (> 15°), with image content placed directly on the road at distances up to 20m in front of the vehicle. This offers a much larger canvas for information to be displayed to the driver, while also enabling them to keep their gaze on the road in front of them. Augmented Reality (AR) is quickly becoming a popular marketing term for devices that attempt to add synthetic information as an overlay to a viewer's field of view. This AR perspective is quickly growing in interest for HUD implementations – assuming the display technology can somehow support it. Fortunately, laser illumination, when combined with DLP technology and other exciting new optical technologies, has the potential to advance these new types of head-up display systems.

Traditional head-up display systems require a relatively large amount of space to implement and thus occupy a significant amount of precious real estate in a vehicle's dash. Figure 5 illustrates the fundamental components of a typical HUD unit.

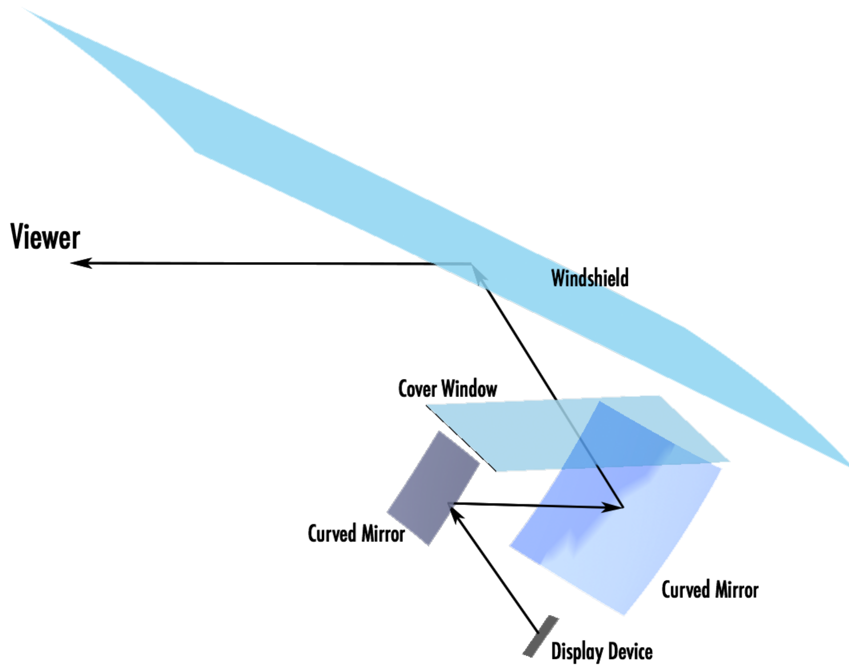

Figure 5. Basic head-up display optical architecture

In this configuration, there is a display device that is imaged thru the use of two or more mirrors to form a virtual “window” directly in front of the driver’s face. This virtual “window” (referred to as the eyebox) is actually the exit pupil of the optical system and the driver must be positioned directly within this exit pupil in order to properly see the virtual image that is formed some distance away. This is essentially equivalent to the familiar example of looking into a telescope, rifle scope, or binoculars where there is a small virtual opening that must be placed very near the user’s eye before any image becomes visible. This principle is important to understand, as it is one of the most significant contributors to the overall size of the optical architecture for a HUD system. For a HUD system, this eyebox must be large enough to not only allow for both eyes to fit within it, but also allow for some variation in eye spacing, head position, driver height, etc. As a result, the eyebox is often as large as 140mm x 60mm and in many cases must be adjusted mechanically to align to the driver’s head position in the vehicle[7]. This large size of the eyebox forces the optical elements of the system to be larger, with significant air spaces between each of the components, resulting in a relatively large optical system. In order to significantly increase FOV and eye box size for AR HUD systems, more space is required for traditional optical approaches, however, space is very limited in the instrument cluster area of the vehicle.

New technologies are being developed that now provide an opportunity to reduce the size of HUD optical architectures. This new technology can also enable larger fields of view and longer viewing image distances without increasing the overall size of the system beyond the current state of the art. One of those new technologies is generically referred to as “waveguides”. While various forms of waveguide technology have been used in optical systems for decades, new manufacturing capabilities have enabled new types of waveguide technology that allow for higher efficiency and improved performance. A waveguide, in its simplest form, is essentially an optical pathway that light can travel thru via multiple reflections. As the light travels thru the waveguide, it reflects at each edge of the waveguide multiple times through total internal reflection (TIR) until exiting the waveguide structure. Figure 6 illustrates the fundamental concept.

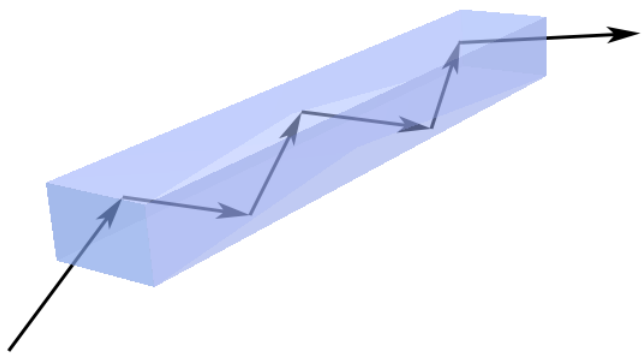

Figure 6. Basic waveguide concept

More advanced waveguide solutions build on this fundamental concept of total internal reflection by incorporating additional structures and interfaces that enable light to enter and exit the waveguide structure in a controlled manner, such that the total area of the light can be expanded in one direction or another as it travels thru the waveguide. This is called "pupil expansion", and it offers the ability to essentially lengthen the distance for a given path of light while preserving its propagation angle – all without increasing the overall volume of the optical system. The net effect of this distance increase is the expansion of one or more dimensions of the light that was provided to the input of the waveguide. Figure 7 illustrates the concept of waveguide pupil expansion.

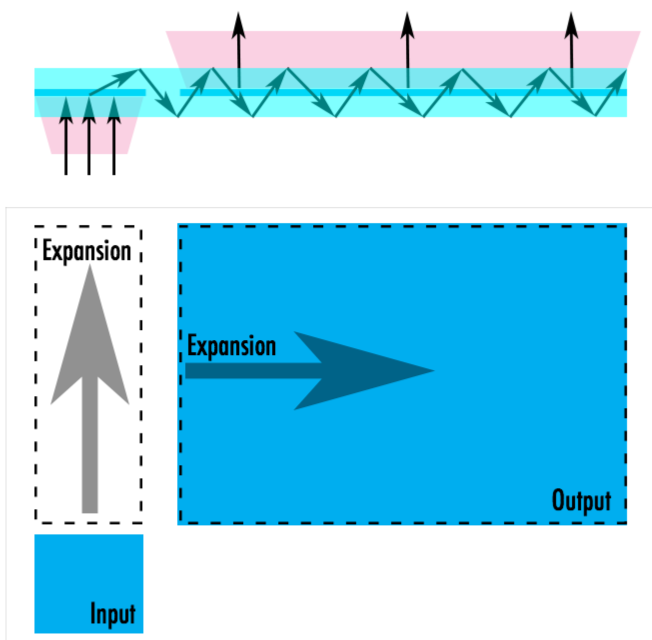

Figure 7. Illustration of simple waveguide expansion

This expansion capability essentially creates an “accordion” effect within the optical architecture and enables a significant amount of potential size reduction. While the specific details of the optical structures that provide this expansion capability are usually proprietary, most of them rely on the following optical principles: diffraction, wavelength diversity, or partial reflection. Diffraction gratings are commonly used and rely on the principles of diffraction. These are essentially a series of repeated microscopic structures printed, etched, or molded into the surface of a given material. Manufacturing these very small structures with high accuracy and quality has improved significantly recently and is now enabling a wide variety of new applications – including near eye displays and head-up displays[8][9][10]. Some manufacturers have developed new technologies that support multiple wavelengths or input angles, and can even be changed dynamically to provide enhanced capabilities. Waveguide technologies are quickly advancing in pursuit of new applications such as head-up displays and even near eye displays.

With waveguide technologies operating at or near the dimensions of the wavelengths of light being used, there are benefits in performance when laser illumination is used. Although broader bandwidth LED illumination can be used, Laser illumination, with its inherent monochromatic properties, allows for higher diffraction efficiencies, reduced scattering losses, and better efficiency overall. When this is combined with the benefits of DLP technology as discussed in previous sections, new possibilities exist for very compact and efficient designs. Figure 8 illustrates the potential size reduction that can be obtained for a head-up display system with comparable capabilities to current solutions available on the market today, using waveguides with laser illumination and DLP technology. This architecture removes the need for large curved mirrors and air space between the mirrors.

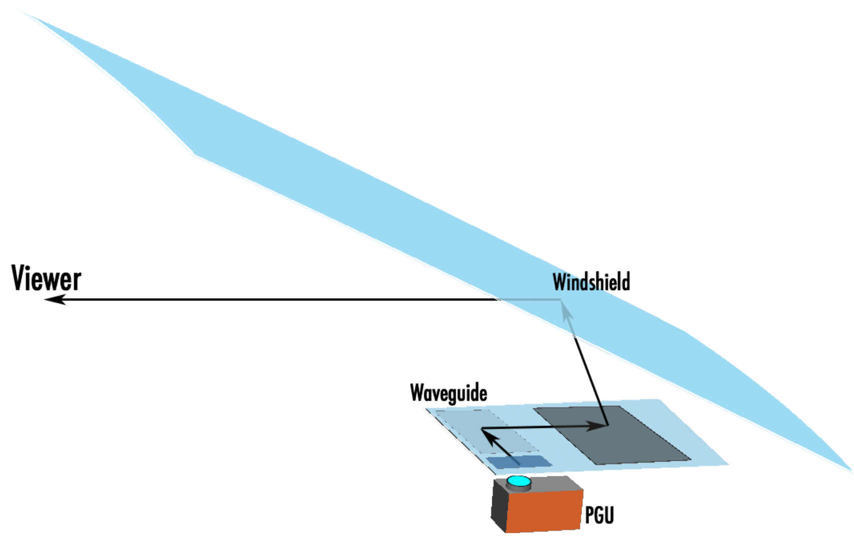

Figure 8. Head-up display optical architecture with waveguide technology

Thus, the resulting size reduction makes it possible to achieve new designs that can provide larger fields of view (> 10-15°) with longer viewing image distances (> 10-20 m).

Another new technology that can also have similar impacts on size and performance for head-up display applications is holographic films. Although holographic recordings were first created back in the 1960’s soon after the creation of the first laser, and as such are certainly not new – recent advancements in polymer films along with new printing techniques have enabled new possibilities for holographic films. Like the microscopic diffractive structures found in many waveguide solutions discussed previously, the structures contained in a holographic recording have the ability to bend light in very unique ways. Most are probably already familiar with the holographic images that have found their way to anti-counterfeit security labels on credit cards and thus have a general understanding of what they look like when used as a 3D image forming media. Holographics can also be used as optical elements, shaping and bending light in very extraordinary ways. In fact, the functionality of multiple traditional optical lens elements can be combined into a single holographic film recording, significantly reducing the overall size of the optical system. From the perspective of reducing the size of a head-up display system, one or more holographic films can replace the functionality of the larger curved mirror elements that are traditionally used, as well as eliminate the need for some of the large air space between the elements. Like waveguide technology, this size reduction can enable new head-up display designs that offer bigger images that are farther away from the viewer, with a total system volume that is significantly less than that of traditional approaches. In order for holographic films to work for head-up display applications, the film is placed directly in the line of sight of the viewer – either on the windshield or on a separate element (combiner glass) just in front of the windshield. While there are challenges with installing films on or within the windshield structure, this approach has the potential to offer a very compact head-up display solution. Since holographic films must be recorded with monochromatic illumination, they naturally perform best when used with monochromatic light in the final application. As such, laser illumination then becomes a desirable candidate as an illumination source for these new designs. Holographic films can also be layered to support multiple wavelengths, offering capability to support full color displays. This multi-layer approach can also be used to provide other unique features such as multiple image planes. For automotive applications, multiple image plane solutions can provide some unique configurations, creating display content that is both near the front of the car as well as farther out over the roadway. This can be accomplished without complex, bulky traditional optical architectures and provides fertile ground for new display possibilities. Figure 9 illustrates the holographic film concept for a head-up display application.

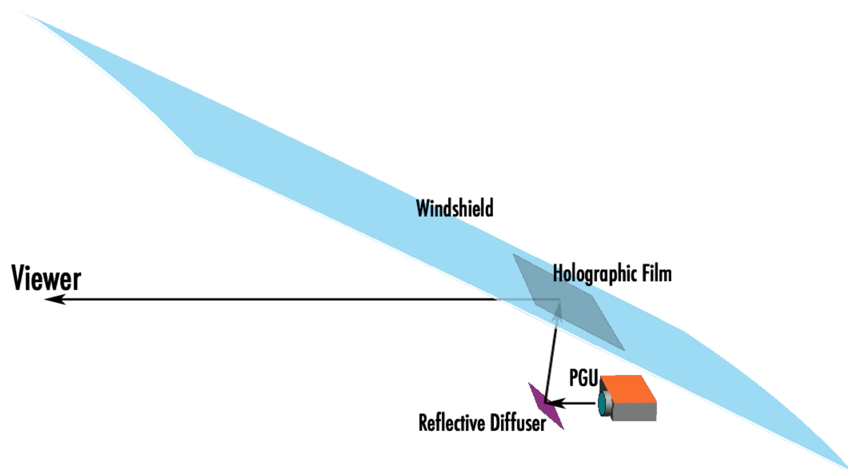

Figure 9. Head-up display optical architecture with holographic film on windshield technology

Waveguide and holographic technologies offer some unique advantages – not only for size reduction, but when combined with the capabilities that both lasers and DLP technology offer together, exciting new capabilities can be enabled for field of view, image distance, brightness, and contrast. Most waveguides and holographic films rely on diffractive properties of light and as such perform best with narrow band or monochromatic illumination – i.e. lasers. With the recent improvements in compact, high power laser illumination technologies, these new technologies have the opportunity to quickly become mainstream enablers for new head-up display designs and have the potential to totally revolutionize the future of head-up display.

5 Color saturation reduces reaction time

Color saturation plays a critical role in the reaction times of human observers; particularly for the color red. It is fairly standard knowledge that less saturated colors appear more gray. A recent study shows that objects that lack saturation actually appear to blend into the background, while more highly saturated colors are perceived as close to the foreground[11]. Highly saturated colors have also been proven to attract observers' attention in relation to their surroundings[12][13].

A study conducted at the National University of Tucumán in Argentina took the effects of color saturation on humans one step further: they found that reaction times are significantly lowered with increased color saturation[14]. In the case of magenta—which is comparable, if not somewhat inferior, to red—reaction times could be lowered by more than 100ms by increasing the saturation from 15% to 50%. This was found to be the case for a variety of luminance conditions; even in cases in which background luminance matched that of the magenta graphic. Similar results were found for the other colors: the more saturated they were, the lower the observer's reaction time and vice versa. Additionally, for most colors, it was important that the saturated color be brighter than the background image in order to decrease reaction time.

As a purely reflective technology, DLP technology can take full advantage of highly saturated solid state light sources including LEDs and lasers. As seen in Table 1 below, DLP HUDs can achieve a red saturation of 91% with LEDs as their light source and virtually 100% with lasers[15].

Table 1. HUD color performance

	Dominant Wavelength (nm)	Saturation (%)
DLP Technology (RGB LED)[16]	R:620	R:91
	G:549	G:75
	B:456	B:95
DLP Technology (RGB Laser)	R:638	R:100
	G:525	G:100
	B:462	B:100

Reaction time can be an important consideration for automotive display systems that are implementing ADAS functions. Thus, leveraging highly saturated light sources for AR HUD systems can add significant benefit.

6 Market adoption and challenges for lasers

The use of lasers in automotive applications is still relatively new. To better understand how the market will likely develop and explore the advantages lasers can offer, it's helpful to look at the consumer and commercial markets. Semiconductor laser diode companies have been investing in these markets since the introduction of the Blue Ray specification in the early 2000's and as a result many of the technological advancements made in these markets can be leveraged by the automotive market.

Let's start by examining the projector market where there has been significant growth in the use of laser based light sources over the last several years. In 2012, lasers represented about 10% of the total solid state illumination sources shipped world wide and has since grown to 24%[17]. Of all the laser projection systems shipped in 2017, DLP represented over 70%[17]. The majority of these projectors are hybrids which do not use individual red, green, and blue lasers. Instead, they either use a blue laser in conjunction with phosphor material to create the red and green colors or they use a red LED for the red illumination. For example, Casio's LampFree projectors create blue and green with a laser phosphor source and red via a red LED. [18]

Table 2. Solid state illumination in projectors[17]

Illumination	2012	2013	2014	2015	2016	2017
Laser	7,215	527	33	36,283	103,226	106,666
Laser/LED	100,428	101,321	102,425	124,920	158,985	170,802
Laser/Phosphor	1,455	6,259	13,482	53,854	167,891	332,874
LED	997,957	739,776	911,611	1,313,127	1,982,854	2,578,945

In high lumen projector applications such as those found in cinema, the operating lifetime of lasers has proved to be a significant advantage over traditional lamp based illumination sources. The operating lifetime of a laser diode can reach 20,000 hours or more in a high lumen projector. Traditional lamp based projectors must change the lamps out every 3,000 to 4,000 hours. Reducing the service intervals not only reduces operating costs, but also proves to be much more environmentally friendly.

Another factor contributing the growth in the use of lasers is the transition from Rec. 709 which defines High Definition (HD) displays to Rec. 2020 which defines 4K/8K Ultra High Definition (UHD) displays. In order to meet the Rec. 2020 color saturation requirements, projectors are using red, green, and blue lasers – as they are the only practical light source that can meet these stringent specs.

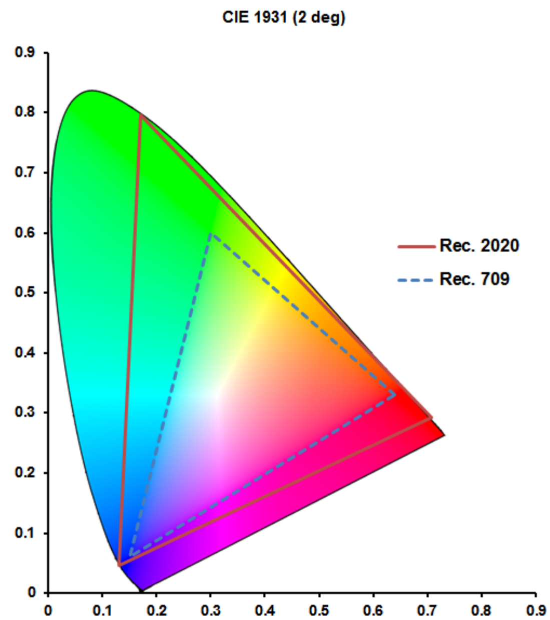

Figure 10. Rec. 2020 vs Rec. 709 color space

Laser based projectors also have an advantage when it comes to size and brightness enabling manufactures to create smaller, brighter, more esthetically differentiated designs. The high efficiency of lasers generates less heat at high brightness levels, reducing the size of the heatsinks and associated projector size. The optical and mechanical package dimensions can also be shrunk as described earlier in this paper.

Another growth vector is the Chinese government's latest 5 year plan which is driving the development and adoption of laser diodes. China's government wants to develop industries around complex, differentiated products and is promoting the use of lasers and the development of laser diode manufacturing technology.

Each laser diode color is based on a unique material set and has different properties such as operating temperature and lifetimes. These different properties create differing challenges for the 3 colors when it comes to automotive qualification. The blue laser diode is the most “robust” automotive laser and when combined with phosphor, can be used to create the white light used in automotive headlight applications. Both Audi and BMW are shipping cars today with laser headlights[19]. Red and green automotive grade lasers have proven more challenging, with less commercial availability and lower operating lifetimes and temperatures (especially red). Low power, single mode RGB lasers will be the first to be released in the automotive market, with the higher power, lower cost multi-mode RGB lasers to follow.

Laser diodes have the same failure modes and gradual lifetime degradation characteristics as LEDs. Unfortunately, they are also subject to Catastrophic Optical Damage (COD) failures which are related to crystalline lattice defects. Laser manufacturers are working to improve the screening and elimination of COD defects, but more work is needed to meet the lifetimes and operating temperatures required for the automotive environment

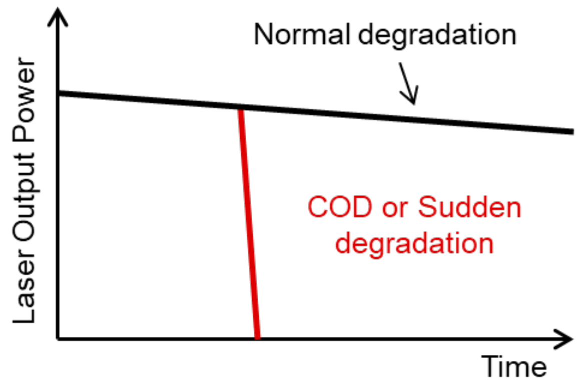

Figure 11. COD degradation mechanism[20]

As demand for automotive lasers increase driven by applications such as holography and waveguide based HUDs it's reasonable to assume the industry will solve the challenges outlined above. It is also reasonable to expect the automotive market to continue to leverage advancements made in the consumer and commercial laser markets. Many of the advantages lasers provide in these markets will be realized in the automotive market as well.

7 Summary

There are numerous advances in laser diode technology development and productization that are now shipping in consumer, commercial, and automotive applications. The most prolific laser based architecture is blue laser hybrid systems (combined with laser phosphor material and/or LEDs) which are already available in automotive headlight applications today. Red and green lasers still have limitations preventing wide adoption into automotive applications. Laser based DLP projection systems can be significantly smaller in mechanical volume, have increased contrast and electrical efficiency, and very high color saturation. When DLP laser project systems are combined with new optical solutions (waveguides or holographic films), these combinations can result in AR HUD systems with much larger field of view, larger eyebox, and long virtual image distance while decreasing the total mechanical volume required. These technologies together can be leveraged by car OEMs to implement true augmented reality ADAS functionality that will revolutionize the way HUD systems are used.

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