Understanding Trade-offs in Microdisplay and Direct-View VR Headset Designs

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Introduction

There is currently some debate about which VR headset architecture will create the "best" images with the "best" form factor at the "right" price. In writing this white paper, we started the process by framing the issues as a choice between microdisplay-based designs vs. direct-view panel designs. But along the way, it became evident that the decision to base the headset design on a microdisplay or a direct view display is not simple. And in fact, is not often the starting point of the decision – something assumed in the beginning. Rather, a well-designed VR headset starts with top level criteria and works its way down to architecture and component decisions. This is also an iterative process so if the original choice of architecture doesn't meet the top level goals, a redesign may be warranted. This top down approach to VR headset design is what we would like to describe in this white paper.

Key Findings

Summarizing the full report, we have concluded that:

- VR headset design consists of dozens of design trade-offs with interplay between optical and electronic elements and their impact on size, weight, ergonomics and performance
- For a given panel resolution, increasing the field of view increases the likelihood of seeing more and more unwanted artifacts.
- All VR headsets today do not have adequate image fidelity. Increasing panel resolution is therefore a key industry need. New 2Kx2K OLED microdisplays are now available.
- OLED displays offer the best performance right now in terms of contrast, response time, and color – either direct view or microdisplay type panels
- OLED microdisplays seem better suited to allow higher resolutions for film-like smoothness and artifact-free wide field-of-view VR headsets
- New, compact optical designs for the OLED microdisplays are helping to reduce size and weight and improve ergonomics
- Mobile VR is likely to drive the market in the future – not PC-tethered designs
- Two new types of VR architecture are emerging: smartphone-tethered and all-in-one designs. OLED microdisplays seem best suited to meet these design needs

High Level Requirements

Good VR headset design starts with top level considerations. These include:

- Target application and customers
- Target cost
- Key specifications and features
- Key ergonomic and comfort requirements
- Additional components and capabilities

The target application must consider if the design is meant for consumer or professional viewing to start. A consumer application will likely target lower cost and lower performance, for example. Professional use may be for production, post production, game development, VR arcade use, training or simulation for commercial or military users and more. These latter are obviously more demanding from a performance and durability point of view. Each application must also consider if the user wants or needs full mobility or if tethering to a PC is acceptable.

VR headsets run the gamut on cost from simples designed to accommodate a user's smartphone to high-end military headsets that can cost over $10K. Consumer focused solutions are going to be less expensive than professional, but the headset is often only part of the solution. A PC, additional sensors/trackers, cameras, accessories and more will often be needed to complete the solution. Designers must consider all of these costs since the cost of the solution is what the end user is concerned with. If the cost of the headset pushes the cost of the system too high, the end user may opt for a lower cost headset or no solution at all.

In terms of performance, design often starts with top level specification goals. Some of these may include:

- Field of View (horizontal, vertical, diagonal)
- Overlap (mono, stereo)
- Focal distance
- Interpupillary distance adjustment
- Resolution per eye
- Pixels per degree (center, corners)
- Refresh rate
- Latency (motion-to-photons)
- Luminance
- Power
- Weight

A careful review of the use case, target customers, price point and competitive products will lead the designer to try to develop a differentiated solution or a me-too solution. These performance parameters offer a lot of ways to differentiate in terms combinations of features or an emphasis on one or two specifications.

The next envelop of considerations is likely to be the additional features of the headset. Here, options might include:

- Camera (one, two)
- Depth sensor
- Inertial motion measurement (3 or 6 degree of freedom)
- Audio speakers
- Connectivity (Bluetooth, wifi, tethered, etc.)
- On-board storage and video processing
- Eye tracking
- External head tracking and markers
- Battery

A smartphone based design can be one of these choices, but clearly the choices here have an impact on size and power as well.

Finally, the design must think about headset comfort and ergonomics. Many VR headsets place a lot of weight in front of the eyes. How long can the user wear the device? Can the weight be more evenly distributed? Can the size and bulk be reduced? Can the headset accommodate user eyeglasses? Factors here include:

- Size
- Weight
- Volume
- Center of gravity
- Comfort of headset on nose and head
- Eye relief
- Eye box

The next phase of the design will likely focus on the optical system architecture and choosing some key components.

There is no doubt that every designer wants to optimize each of these specification parameters, but the reality is that tradeoffs need to be made. While the above describes one design approach to a VR headset, many other methods can be employed as well. But what will be common is the need to evaluate the many trade-offs in these parameters to meet the top level objectives of the product. How this trade-off analysis is done will vary greatly too.

Optical Overview

Reality Types

Sometimes, there can be confusion about the terms virtual reality, augmented reality and mixed reality. Below are the definitions we subscribe to:

- Virtual Reality (VR) – an immersive environment where the outside world is not visible. Binocular images for both eyes (2D or 3D) can be computer generated or video based and are designed to fill a wide field of view with 360-degree audio as well. Typical VR headsets include head tracking technology to orient the user in the virtual world

- Augmented Reality (AR) – A transparent display solution that adds virtual objects, typically computer generated, to the real world with both being visible simultaneously. Implementations can include monocular or binocular head-mounted display systems, phone or tablet-based solutions. The orientation of the head/display is tracked to present a view of the real world and synthetic objects.
- Mixed Reality (MR) – A nominally occlusive immersive environment using a head mounted display solution with images for both eyes (2D or 3D), but with the addition of one or more cameras on the headset. This allows the user to see the real world in front of them, but as a video image with synthetic objects added to this image. Head tracking and 360-degree audio may be part of the solution as well.

In this paper, we will focus on VR or MR solution.

Direct-View vs. Microdisplay Panels

There are two basic classes of display to power VR headsets: direct-view display and microdisplay. Microdisplays typically less than 1" in diagonal size are almost always used with some sort of magnifying optics whereas larger direct-view types are designed to be viewable with the naked eye. Direct-view displays are used in cell phones, tablets, laptops, monitors and TVs, whereas microdisplays power projectors and viewfinders.

VR headsets have been around for a long time and early models used microdisplays to power them. In the last few years, direct-view panels have been used. Direct view displays have bigger pixels than microdisplays and the panels are bigger. One good way to compare them is on a pixels per inch (ppi) basis.

- Direct-view displays have 400 to 800 ppi and range in size from 3.5" to 5.5"
- Microdisplays have 2,000 to 3,300 ppi and range in size from 0.2" to 1"

VR headsets must magnify the display image to create a wide field of wide – even direct-view types.

- Direct-view displays require less magnification with large optics
- Microdisplays require more magnification with somewhat smaller optics, which is very challenging to get a large field of view. Microdisplays with much higher ppi can provide much smoother image than direct-view displays for VR headsets.

Size, weight and power are other differences between these two types of display. This can have a big impact on the overall size, weight, bulk and ergonomics of the VR headset.

- Direct-view displays are bigger, heavier and more power hungry than microdisplays

Microdisplay Types

DLP

The DLP microdisplay is offered only by Texas Instruments. For head-mounted display and Heads-up Display applications, they offer their TRP type device in a variety of sizes and resolutions. The Avegant Glyph is an example of a headset using a DLP engine, but with a limited 40-degree field of view.

The DLP imager is composed of a matrix of tiny mirrors that can be flipped to one state or another, reflecting light to the eyes or away from them. The mirrors are fabricated in a MEMS foundry on top of a silicon control matrix, fabricated in a conventional silicon foundry. Special packaging is needed to keep the mirrors operating in a special atmosphere. A separate controller ASIC is also needed as the device operates as a series of pulsed light signals. It is a single chip solution meaning red, green and blue light is flashed on the display in time sequence. The eye integrates these fast flashes to create a smooth motion image. These updates must be quite fast in any field-sequential-color system to avoid artifacts like color breakup (rainbowing on some moving objects).

The DLP device has the advantage of being able to reflect unpolarized light making it more optically efficient than LCoS or LCD designs which use polarization. It also has a large fill factor. One disadvantage of the DLP is the difficulty in designing a high-magnification lens since a prism in front of the display is needed to couple light onto the panel and to gather “off-state” light to an absorber. Another disadvantage is the one-frame latency required to convert the standard video format to a color sequential format.

LCD

LCDs are transmissive devices that use red, green and blue color filters over the sub-pixels. This eliminates any color break-up issues, but can sacrifice resolution as RGB elements are now created spatially instead of temporally.

Companies like Sony and Epson fabricate their transmissive LCD microdisplays on quartz crystals using a high temperature poly silicon process to get the high density of sub-pixels needed. Kopin fabricates their display electronics on single-crystal silicon and transfers them to glass using a special lift-off process.

The ability to use single-crystal silicon or high temperature poly silicon means that some of the drive electronics can be incorporated onto the display, increasing reliability and lowering interconnections and costs.

Compared to DLP, the LCD uses backlight illumination, making it easier to design high-magnification optics. However, LCD microdisplays suffer from a lower fill factor than reflective or emissive microdisplays which means the pixel structure will be more visible for comparable alternatives (the screen door effect). Other disadvantages are the lower contrast ratio (a few hundred) and longer response time (> 10 ms).

OLED

OLED microdisplays are fabricated on silicon backplanes with a stack of OLED and other materials above. OLEDs must be very well protected from moisture and oxygen, requiring very good packaging.

Most of the OLED microdisplays use a white emissive layer that is topped with an array of RGB color filters – just like with LCDs. Sometimes a RGBW structure is used with the W representing white or essentially a clear filter. This white sub-pixel element allows for a brighter display, but may sacrifice color gamut when engaged.

Unlike the other display types, OLEDs are emissive so light is only created at the desired pixels. This can lead to displays with the best contrast. In addition, the response time is very fast (micro seconds). The optics design would be similar to the LCD case.

The second type is a one where each red, green and blue sub-pixel emits it own light directly so no color filter is needed. The white emitter with color filter approach is an easier structure to manufacture than one that creates individual red, green and blue OLED sub-pixel emitters. However, the direct RGB type offers higher efficiency and may be preferred for mobile applications if the manufacturing issue is resolved.

LCoS

Liquid Crystal on Silicon (LCoS) uses a silicon backplane fabricated in a foundry (with special processes) and a second foundry/facility to create the liquid crystal layer. Device electronics can be integrated on chip and high densities with minimal screen door effect are possible.

LCoS is a reflective device type which requires polarized light to operate. A prism or beamsplitter type device is needed to couple light into and out of the panel, which operates in a color sequential mode. Unless the panel operates very fast, color break up is a concern. A variation of LCoS imager based on ferroelectric liquid crystal, operates at much higher frame rates and has essentially eliminated color break up (although at some loss of optical efficiency).

LCoS has the advantage of a large fill factor, but has the disadvantages of optics design difficulty and one-frame latency, similar to DLP.

Summary

Doing a simple strengths and weakness comparison between these microdisplay types is not straightforward as there are many companies and within each category, there are variations in capabilities and technologies. As we have noted, VR headset design must look at many variables and it is a series of trade off analyses that must be done to find the solution that best fits the objectives of the product development. In general, however, the OLED microdisplay seems to be the best choice for the VR application.

Direct-View Types

LCD

Direct-view LCDs operate in the same way as their microdisplay cousins, but with a much lower pixel density. The backplane is made on a glass substrate using different manufacturing techniques. A layer of liquid crystal materials covers this backplane with RGB color filters above. A backlight unit provides the white light.

For VR applications, high density smartphone class displays made with low temperature polysilicon backplane fabrication process are used with magnifying optics. The big advantage of these displays is availability – they are made in the millions for smartphones so they are relatively inexpensive. However, the LCDs have a lower contrast ratio and longer response time, which will compromise the VR experience.

OLED

The same issue of pixel density applies to OLED direct-view vs. microdisplay-based panels. Instead of fabricating the OLED layers on top of silicon backplane, OLED direct-view panels use either glass or flexible plastic substrates with the drive matrix constructed with ZnO or low temperature poly silicon processes.

Unlike their microdisplay cousins, most direct-view OLED panels are believed to be fabricated by creating individual red, green and blue emitting sub-pixels. However, there is a difference in the way these sub-pixels are arranged and driven.

For example, we believe that the Sony PlayStation VR headset uses a single ~5.7" OLED panel with sub-pixels arranged in the traditional "RGB stripe" pattern, as shown in the right side of Figure 1. However, for the HTC Vive and Oculus CV1, there are two OLED panels about 3.6" in diagonal. These are believed to be sourced from Samsung and use the so-called Pentile sub-pixel arrangement as noted in the left side of Figure 1. The Pentile pattern features a full resolution array of green sub-pixels but a half resolution array of red and green sub-pixels. A full color image with the same resolution as the green sub-pixels is created by a processing technique called sub-pixel rendering. Essentially, this is a technique that creates full color pixels by borrowing red and blue sub-pixels surrounding the green sub-pixel and applying a complex algorithm. Samsung does this to reduce the number of interconnects and reduce panel cost and claims the panels meet definitions of resolution as defined by the International Committee on Display Metrology (ICDM).

While fill factor is not high in these panels, the surrounding black material helps to create a high contrast image. But the smaller fill factor (active emitting area) of the Pentile pattern compared to the conventional RGB stripe may increase the ability to see individual pixels (the screen door effect), especially on very wide field of view headsets.

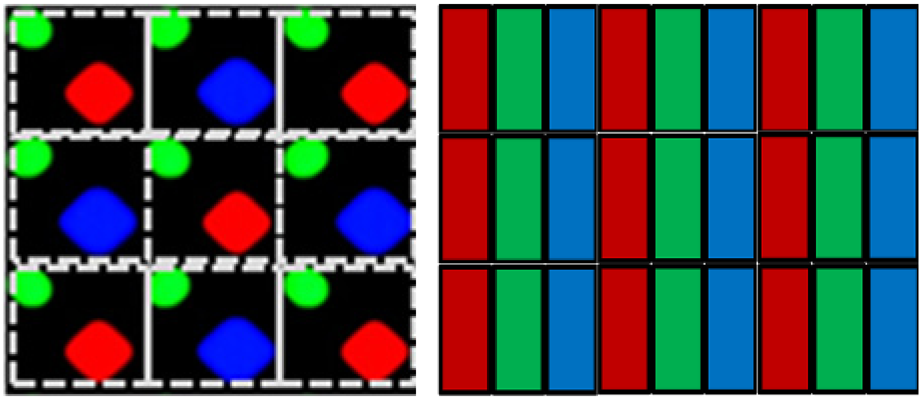

Figure 1: Pentile Diamond pixel architecture with sub-pixel rendering (left) and conventional RGB stripe sub-pixel arrangement (right)

Optics Considerations

Whatever the display choice, optics are needed to create a wide field of view (WFOV) image. Most VR headsets today strive for at least a 90-degree horizontal field of view. If there are not enough pixels in your display (or displays), then the pixel structure may be evident, thus compromising image quality. Clearly, the more pixels the better for image quality, but that involves tradeoffs.

Field of View

The Field of View (FOV) of the VR headset is a common specification but care must be taken in understanding this spec. For example, some headset makers describe the field of view as the *diagonal* FOV, while others mean the *horizontal* FOV. The FOV generally refers to what both eyes see. Most VR headsets overlap the images from the left and right eyes, so each eye sees the same FOV. But the optics don't have to be designed this way – they can have a partial overlap area, which would expand the overall FOV. You need to be clear which FOV the spec refers to as well as the overlap if you want to compare headsets.

Field of view can be increased by moving the eye closer to the optics or making the optics bigger. Moving the eye close to the optics sounds like a good idea, but you want to have good eye relief (separation between the optics and eye) to accommodate eyeglasses if your optic don't have a focus adjustment. Making the optics bigger impacts size and weight. In addition, moving closer to the optic may increase the FOV, but the image may become distorted. If positioned to far away, vignetting will occur, reducing the FOV. With a narrow FOV, you are not seeing all the pixels either. Plus, the left and right eye's FOVs characteristics may not be the same. There is an eye relief distance at which the FOV is optimal and at which point any distortions are properly compensated for. This is also the point where the FOV should be measured.

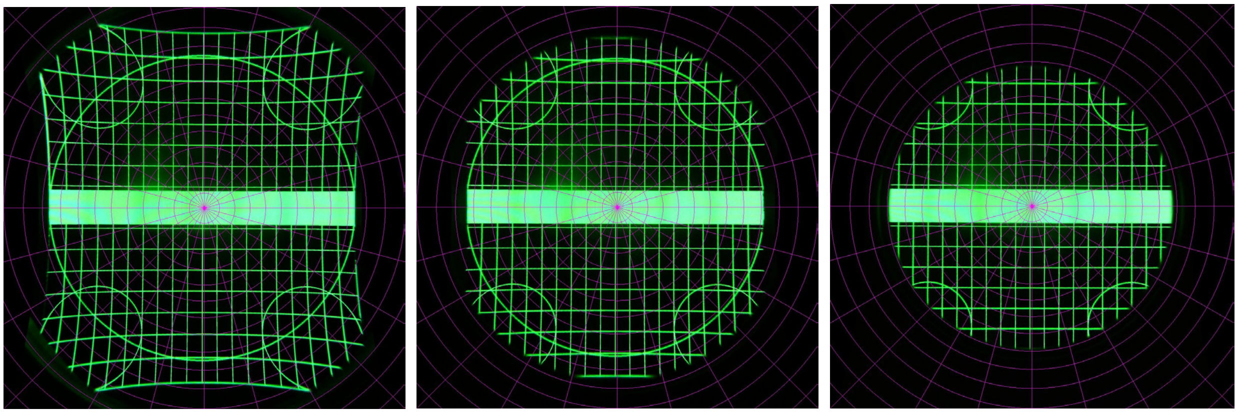

Figure 2: Effect of changing the eye-to-lens distance is reduced FOV. Images show the FOV for the Oculus Rift DK2 headset at a eye-to-lens distance of 5mm (l), 10mm (c) and 15mm (r) (Source: doc-ok.org)

<u>*Resolution*</u>

Resolution may also be confusing. Some headsets feature a single display while others use two dedicated displays. Often, the resolution of the single display (in case of using a single display) or the sum of resolutions of the two displays is used to describe the resolution. Care must be taken to calculate the specifications on a per eye basis.

<u>*Pixels Per Degree*</u>

One way to consider image quality is the pixels per degree (PPD) metric. For example, if you want a 100 degree horizontal field of view and use a single panel with 1080 pixels in the horizontal direction, you get 11 pixels per degree per eye if the optics are perfect and your eye is in the optimal lens-to-eye position. The horizontal PPD <u>per eye</u> of the HTC Vive, Oculus CV1 and PlayStation VR headsets are all in the 10 to 15 range today.

Kopin has introduced a panel with 2048 x 2048 pixels with an optic that delivers a 64-degree horizontal FOV (90-degree diagonal). This yields a PPD of 32, a noticeable and significant increase in image fidelity. It plans a future display with 3072 x 3072 resolution and new optic to deliver a 85 degree horizontal FOV (120 degree diagonal FOV) that will yield a PPD of 36.

But the magnification optics are never perfect so there will be a reduction in the actual visible PPD value. Image quality is degraded by many design choices. Some of the effects of these degradations can be measured, some not so much. These are discussed below.

<u>*Visual Acuity*</u>

We are all familiar with the Snellen eye chart to determine our visual acuity. We all know that 20/20 is good vision, but what does that mean exactly. According to Wikipedia, "Snellen defined "standard vision" as the ability to recognize one of his optotypes when it subtended 5 minutes of arc. Thus the optotype can only be recognized if the person viewing it can discriminate a spatial pattern separated by a visual angle of 1 minute of arc." In other words, a person with 20/20 vision can see two separate lines that are one arc minute wide and separated by 1.75mm at a distance of 20 feet. A person with 20/40 vision can see separated lines at 20 feet that a person with 20/20 vision can see at 40 feet and so on.

Visual acuity can be calculated based upon the pixels per degree that the VR headset creates. Assuming perfect optics, the current VR headsets from Sony, HTC and Oculus are in the 20/80 range. This clearly shows that we have a way to go to get to optical solutions that come close to the visual clarity of most people's eye.

The new Kopin OLED displays described above will obtain better than 20/40 visual acuity, a marked improvement.

Another aspect of acuity that is not as often discussed is Vernier acuity, sometimes called hyperacuity. This refers to the ability to see slight separations in lines. In other words, the human visual system is very good at seeing slight differences in alignments, which much higher precision that the visual acuity measure might suggest.

Why is this important - because it is an element to our perception of the sharpness of the image?

<u>*MTF*</u>

Modulation Transfer Function (MTF) measures the contrast performance as a function of resolution. It is the ability to distinguish a black and white pair of lines as the separation between them gets smaller and smaller. Not only does the separation of the lines diminish, but the contrast between the two lines declines at the same time.

MTF measures the spatial frequencies that the display and optics combination are capable of transmitting. The spatial frequency response is related to the PPD specification but takes into account the degradation effect of the optics.

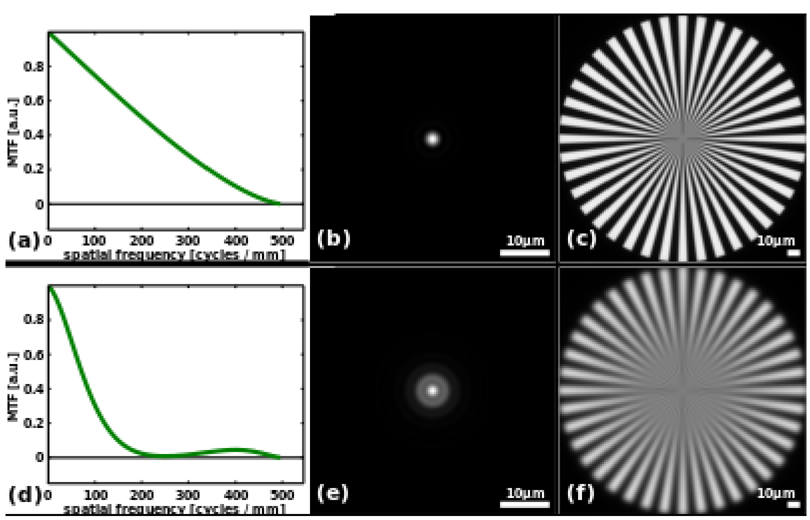

Figure 3: Modulation Transfer Function (MTF) provides a measure of the display and optics quality. Top images show excellent MTF while bottom images show a poor MTF (inability to pass high frequency elements to create sharp edges) (source: Wikipedia)

MTF is actually a good overall measure of the display resolution and optical system combined. It provides an understanding of the "resolution to the eye" as well as the ability of the display and optics to reproduce fine details and sharp edges – something you might think of as the "crispness" of the image.

Mura

Mura is non-uniformity of the display which can be visible on uniformly colors parts of an image. Direct-view OLED displays fabricated on glass using low temperature poly Si backplane are quite susceptible to display mura as slight variations in processing lead to changes in the pixel current, which manifests itself as non-uniformities, as shown in Figure 4. Such non-uniformities can be corrected by measuring them and then created a compensation look-up table that is applied to every image presented to the display. Budget VR headset solutions may not do this correction. OLED microdisplays fabricated on single-crystal Si, however, are mostly free of mura.

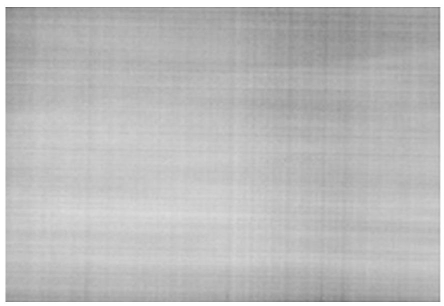

Figure 4: OLED display with uncorrected line mura (source: Radiant Vision Systems)

Flare

Flare is light that is reflected off of surfaces that is visible, but unwanted. Some optics, like Fresnel lenses, are more prone to flare than others. One way to test this is to display white text (Glare Text in Figure 5 below) on a black background. Notice the edges of the Fresnel lens are quite visible.

Figure 5: Flare Test (even though the image says glare - source: Doc-Ok.org)

Crepuscular rays

Crespuscular ray are streaks of light in an image that should not be there. These occur in nature and are sometimes called God rays or Sun rays (the streaks of light coming through breaks in the clouds). In a VR headset, they might manifest as streaks of light coming from bright text, for example.

Figure 6: Crespuscular Rays (Source: Doc-Ok.org)

Screen Door Effect

The Screen Door Effect (SDE) is when the image has a mesh pattern over it that is like looking at the world through a screen door. What you are seeing is the pixel structure of the underlying display as only part of the surface of the pixel is emitting or transmitting light. The screen door effect can result from several factors: low fill factor, spatial vs. temporal color methods, the color being display, and/or high magnification.

Figure 7: The Screen Door Effect on the Oculus DK2 (left) and CV1 (right) VR headsets (Source: AtomicSuperman)

Fill factor refers to the amount of the display area that can be used to generate, transmit or reflect light. DLP and LCOS displays have a high fill factor meaning ~95% of the area is used to reflect light. High density LCD and OLED displays for VR applications usually have a lower fill factor, and it is much lower for the direct-view OLED display using the Pentile structure shown in Figure 1.

Figure 7 shows the effect on the oculus DK2 and newer CV1 models. The DK2 used an LCD with lower resolution while the CV1 using an OLED display with the Pentile structure (Figure 1), which greatly reduces the SDE, but also appears to be a bit "softer."

Another factor in SDE is magnification. Clearly, the more magnified the image the more the pixel structure can become visible. This is one of the dangers of very wide field of view VR headsets – you start to see pixel and the screen door effect.

Additionally, the way colors are displayed and their color can impact the screen door effect as well. For example, with an LCoS device, colors are displayed in a color sequential manner so each color has the same fill factor.

In spatially patterned displays with color filters or RGB emitting areas, the color white will have a bigger fill factor (all red, green and blue sub-pixels are used to create white) compared to a single primary color (where only a 1/3 of the subpixels are used). The situation may be worse on Samsung OLED Pentile panels where there are twice as many green sub-pixels as red or blue (Figure 1).

Geometric Distortions and Chromatic Aberrations

No optical system creates a perfect image. There will be some distortion of the image such that a rectilinear grid may not be perfectly straight and perfectly proportioned. These are geometric distortions which can be corrected by adding additional optical elements. This is the best approach, but has the trade-off in cost, size and weight of the optical system.

The other way to correct for geometric distortion is electronic warping of the image. Here, the idea is to first understand how the optics are distorting the image, then apply an inverse distortion to create geometrically correct images. This eliminates the need for additional optical elements, but adds processing and can reduce to crispness of the image – a trade off most VR headset designers would consider a good idea.

Chromatic aberrations result from light of different wavelengths focusing on slightly different points. This may be visible as a slight "rainbowing" of a white line, for example. This is typically corrected with optical elements.

Additional coatings may also be considered to reduce flare, unwanted reflections and to eliminate non-visible light.

In general, the better the image quality the more expensive, bulky and heavy the optics become, so this is a major design tradeoff area of consideration.

Functional & Ergonomic Optical Considerations

Some optical design choices affect the ergonomics of the headset and the functionality of it as well.

Interpupillary Adjustment

The interpupillary distance, sometimes called IPD, is the distance between the center of the optics for the left and right eyes. In some headsets, this distance is fixed and in others, it is adjustable.

A fixed IPD is less expensive than an adjustable one, but it has limitations as well. At what distance should you fix it? In humans, the IPD can vary between the genders, races and ages. If you fix the distance, then you will want to design your optics with a large eye box (discussed below) to accommodate variations in the user population.

A variable IPD allows the user to set the separation according to their eyes, but the range of adjustment must be decided here as well. Designers may be able to get away with a smaller eye box in this case as there is some external adjustment to get the optics positioned correctly.

Eye Relief and Eye Box

The eye box is defined as the physical volume over which the eye can see the full field of view. This is really a volume having x, y and z components, but it is generally expressed as a few mm of horizontal travel, for example. The bigger the eye box the easier it is to see the full image allowing for faster set up and better accounting for variations in human IPD and positioning on the head.

Eye relief refers to the distance from the front of the optics to the sweet spot of best viewing. More eye relief is less claustrophobic and allows for the user to wear eye glasses if needed. The drawback is this it generally pushes the optical system further away from the eyes, putting more weight forward on the head, which is not desirable.

If the optics have a focus adjustment, the user may not need to wear their eye glasses so the eye relief can be smaller. While this has some advantages from the users' point of view, the added space and weight of the focus adjustment often makes it a wash in terms of position of optics on the head compared to designs with no focus and bigger eye relief.

Focus Adjustment

These are optical elements that allow the user to change the focus of the image for each eye independently. This is desirable so user don't have to wear their prescription eye glasses, but as mentioned above, it comes with a cost, weight and center of gravity penalty. On the other hand, it focus adjustments can't correct for astigmatism that many/most eye glasses will also be correcting for.

Other Image Quality Factors

Most of the factors discussed in this section are the result of the choices made in other sensors and in the image processing pipeline. However, some are related to the choice of the display as well.

Frame Rate

Frame rate refers to the rate at which the display refreshes all the pixels. In VR, a refresh rate of 90 Hz is becoming standard with some moving to 120 Hz. In general, the faster the refresh rate the fewer motion artifacts will be evident.

However, one must be careful to distinguish between the display frame rate and the content frame rate. Video content frame rate can vary from 24, 25 or 30 frame per second to 50 or 60 frames per second, along with fractional derivatives. Animated or computer generated content generally runs at 30 or 60 frames per second (fps), but some VR content can be designed to natively render at 90 fps, and in the future, perhaps 120 fps. Higher frame rates require much more powerful CPU and GPU solutions, however.

If the incoming video content was not rendered at 90 or 120 fps or if the CPU/GPU rendering the CG content is not powerful enough to render at 90 or 120 fps, image processing electronics designers have two choices: Multi-frame flashing or motion interpolation.

Higher frame rates are important to help reduce the motion-to-photon latency specification. This is one part of this processing chain, but an important one that OLED displays can help optimize.

Multi-frame Flashing

With this technique, the frame rate of the incoming content is lower than the frame rate of the display. If the frame rate of the display is an even multiple of the frame rate of the content, then a simple “flashing” technique can be used.

For example, if the incoming content was produced at 30 fps, then the same frame can be flashed three or four time for displays that run at 90 or 120 fps. If the incoming content is at 60 fps, it can be flashed twice for 120 fps displays.

But 60 fps content refreshed on a 90 fps display requires different processing. One technique is similar to what used to go from 24 fps source material to 60 fps display: a 3:2 pulldown method. The idea is to flash the first incoming frame twice; the second frame three times, the third frame twice and so on.

This works, but can introduce a phenomenon known as judder. This is a kind of noticeable jerky movement because the captured frames are being displayed in an uneven manner. It is most noticeable in slow steady camera movements that are not smooth.

Motion Compensation

Note that in the multi-frame flashing approach, no image processing is applied so any temporal artifacts that are in the original content will appear even if they are flashed at a higher rate. To address this issue, motion compensation algorithms were developed. The idea here is to generate an intermediate frame that is displayed between two original frames.

For example, if the content is at 30 fps and the display is refreshing at 90 fps, then the original frame is display first, then two motion interpolated frames, followed by another original frame.

Many different algorithms exist for creating these motion interpolated frames which vary from poor to excellent. On video, some have complained that poor processing can create a look that is referred to as "soap opera effect" as it has a cheap interlaced camera appearance. Some have also noted tearing in the image.

Most of these artifacts are on video sources and the algorithms have improved immensely in the last 10 years. They can also be applied to CG content where they should work well. Some VR headset companies already employ motion compensation techniques for content that cannot natively run at 90 fps.

Motion Blur

Motion blur occurs when an object moves too quickly and is not sharp, the camera moves too quickly, or with VR, the head moves too quickly.

Motion blur from camera movement is either poor technique or done on purpose to give it a cinematic look. This is not generally a good idea in an immersive VR environment.

Moving objects that blur in an otherwise stationary shot are impacted by several factors. One is the capture frame rate. 60 fps capture will have less blur with moving objects than the same scene captured at 24 fps. Secondly, the type of display also matters as well. LCD displays typically will exhibit more motion blur than an OLED or DLP display solution as these latter displays have faster response times than LCDs. In addition, LCDs and OLED displays are a sample-and-hold type display system, which is more prone to motion blur.

LCDs have addressed this deficiency in two ways. One method is called "black frame insertion" which literally adds a completely black image between each video image. The cuts the persistence of the image leading to a perception of less blur.

The other technique is to force the liquid crystal material to have a faster response time. This is called overdriving and basically inserts a pulse at the beginning of the frame to quickly drive the pixel on. This works well for some scenes, but not very well for subtle changes in color or luminance (grey-to-grey).

In general, higher frame rate capture and display is the best solution to reducing motion blur.

Motion-to-Photon Latency

When the head moves to quickly in VR, the motion blur can be caused by the display, but may also be caused by the processing electronics pipeline. This is often described as the motion-to-photon latency. If you turn your head and there is too much of a delay, it can induce nausea.

Solving this problem is done with a good choice of sensors, video processing, display processing and fast refresh rate displays.

Color Gamut

The colors that the VR headset can display is obviously an important feature, but this has not really been a focus to date. In fact, we have seen little in the way of specifications. We suspect most are achieving close to the HD specification, the BT.709 or sRGB color gamut, but this is unconfirmed. Modern UHD TVs are already specifying even wider color gamuts like DCI-P3 and ultimately, BT.2020. The color can also be degraded by the poor optics. VR displays have a ways to go to reach these levels.

Contrast

Contrast is a key parameter in image quality that may or may not be specified for the headset. This is the ability to deliver dark black tone and bright white tones within the frame. The measurement of contrast sounds simple, but since OLEDs are emissive, one might measure a display with infinite contrast due to the zero light output in the black state. As a result, the International Committee on Display Metrology (ICDM) recommends that the black level be measured at the first step above a reference no-signal black level to ensure an infinite contrast is not reported.

In the TV space, there is much emphasis on this parameter also known as high dynamic range. This, combined with a wider color gamut, creates a step change in image quality.

But the contrast and color gamut specification does not tell the full story. For example, how accurate does the display render the luminance and colors over it full range compared to a standard like sRGB? With OLEDs, it is often very hard to correctly render the darkest tones as there is variability in the currents that drive each pixel, so the entire black level is raised. This often results in "crushing the blacks" or a big step from no signal black to the first illuminated black code value.

We suspect the variations will be proportional to the area of the display, meaning microdisplays should have less variation than direct-view OLED panels meaning better control over these dark grey levels

To date, we have not seen much emphasis on this aspect of image quality in the VR market, but maybe this will gain more attention in the future.

Luminance

Luminance or brightness is another rarely discussed specification. In reality, VR headsets don't need that much luminance as it is an immersive enclosed environment (not the case for augmented reality where high luminance is needed).

Luminance on the order of 30 to 50 nits to the eye is usually acceptable. Given the losses in the optical system, displays with around 200 nits are generally acceptable and available.

One aspect that we have not heard addressed however is how the image might be adjusted for these low light levels. By this I mean that our perception of color in dim environments is different than in bright environments. For example, the perception of the color of a yellow flower is different in bright sunlight is different than in dim illumination. At midday, it appears yellow, but when there only a little daylight left, it may appear brown. The color of the flower hasn't changed but our perception of its color has.

It may be necessary for VR content to be adjusted or regarded for the adaption of our eyes in the VR headset. Perhaps this is being done, or it is not necessary – I have just not heard it discussed at all.

3D

VR headsets have separate optics for the left and right eye, so they have the ability to display stereoscopic 3D images. Not all VR content is displayed with 3D parallax, but a lot is.

It is well known that there can be eye strain and nausea issues with poorly created or display 3D content. Factors like the 3D volume and offset from the screen plane don't necessarily impact image quality, but they can impact a user's reaction to the content.

This is a deep and complex topic area and we are aware of only one study that evaluated test subjects to 3D VR content (The Korea University College of Medicine in Seoul study was reported by Healio Ocular Surgery News and published in the Journal of Pediatric Ophthalmology and Strabismus). In their study they had 60 volunteers in the age group from 13 to 18 years watch either a 3D movie or try a virtual reality experience. After 30 minutes of watching they did not observe any change in spherical equivalent, near point of accommodation and stereo acuity. They did however observe transient myopic shifts of 17.2% to 30% in both the virtual reality and three-dimensional movie viewers. In no case did this last more than 40 minutes. They also found a very slight esopheric shift (crossed eyes) directly after watching the head mounted displays.

While this sounds encouraging, the subjects are all quite young, the exposure time not that long, the sample was small and it is unclear if any participants had vision issues to begin with. More work is needed in this area. We are aware of one study with a University that is being considered at this time, so perhaps others will be done too.

To be clear, all current VR headsets create stereoscopic images that will inherently produce eyestrain due to the conflict between vergence and accommodation. This conflict arises because our eyes want to focus on the virtual image plane but toe-in to look at nearer objects (in front of the screen plane). Multi-focal displays, light field displays and eventually holographic displays will alleviate this physiological contributor to eye fatigue.

VR Optical Architectures

Overview

In this section we will introduce two microdisplay-based optical solutions for VR and analyze their use for three different design scenarios. First, we will introduce the key components of the optical design, the Pancake optics, Pantile optics and 2Kx2K OLED microdisplay all from Kopin. Then, we will discuss the design trade-offs in different architectures: PC-based tethered, Mobile-tethered and All-in-one VR.

2Kx2K OLED Microdisplay

Kopin has developed a new OLED microdisplay with a diagonal size of 1" and a resolution of 2048 x 2048, which is the highest resolution microdisplay. Two of these are needed to a VR headset and they can be operated at a frame rate of up to 120 Hz.

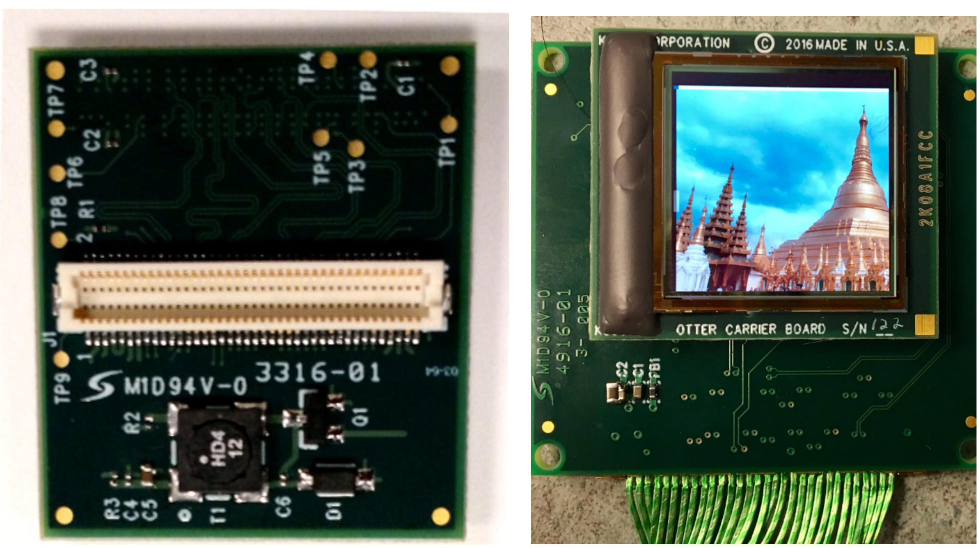

Figure 8: Kopin's 2Kx2K OLED-on-Silicon Microdisplay

The display is an OLED-on-silicon type (Figure 8) that uses a white emitting OLED material with RGB stripe color filters. The very high 2900 ppi with high fill factor allows a very smooth, lifelike image even when magnified to a large FOV. Kopin will manufacture this display using a new fabless model for both the silicon backplane and OLED frontplane. Branded as the Lightning OLED series, the new panel joins additional microdisplays the company offers using LCD and LCoS technology. Kopin also supplies optical modules to serve various commercial, military and consumer electronics segments.

Key specifications of the Lightning display are noted in the table below.

Item	Current	Target
Format	2048 × RGB × 2048	
Color dot pitch	2.88 × 8.64 µm	
Image diagonal	0.99 in	
Frame rate	Up to 120 Hz	
Color Gamut (% sRGB)	72%	100%
Contrast ratio	3,000	10,000
Brightness (nits)	150	> 300
Brightness Uniformity		>85%
Response on time (µs)		< 10
Video input	25-pair mini-LVDS	
OLED Power Consumption	<500 mW	
Process	1.2V / 5V	
Input Formats	24-bit RGB, 24-bit YCbCr 4:4:4, or 16-bit YCbCr 4:2:2	

Table 1: Summary of key Specifications for the OLED Lightning Display

The key advancements represented by this Lightning panel are the high 2Kx2K resolution per eye; the 120 Hz frame rate and the very fast display response time of 10 microseconds – a key ingredient in monition-to-photon latency calculations for the VR headset system. In addition, the low 500mW power consumption is estimated to be about half of comparable displays.

For comparison, the HTC Vive and Oculus Rift both use two Samsung direct-view OLED panels with a Pentile pixel structure and 1200x1080 resolution per eye, refreshed at 90 Hz. The PlayStation VR headset also features a direct-view OLED panel, but with conventional RGB pixel structure and 960x1080 resolution per eye, refreshed at 90 or 120 Hz. Two Kopin 2Kx2K displays will be used for a VR headset, and the increased resolution and frame rate will clearly improve image quality.

Pantile and Pancake Optics

To create the optical module for a VR headset, Kopin has developed two optical designs for the 2Kx2K Lightning panel. The key features of these two optical solutions are shown in Table 2 below.

Lens Attribute	PanTile (2 versions)	Pancake
Diagonal Field of View	80 – 90 degrees (potential for 100 degrees)	90-100 degrees (70 degree on Demo)
Eye Box	> 8 mm	> 10 mm
Eye Relief	15 mm	17 mm
Resolution	Suitable for 2K x 2K	Suitable for 2K x 2K
Color	Good color correction	Good color correction
Thickness	< 30 mm (front to OLED)	< 20 mm (front to OLED)
Optical efficiency	> 80%	10 - 20%
Distortion (uncorrected)	25 – 40%	< 15%

Table 2: Summary of Pantile and Pancake Optical Module Performance

Figure 9: Comparison of Pancake (left) and Pantile (right) Optical Modules to the GearVR Headset

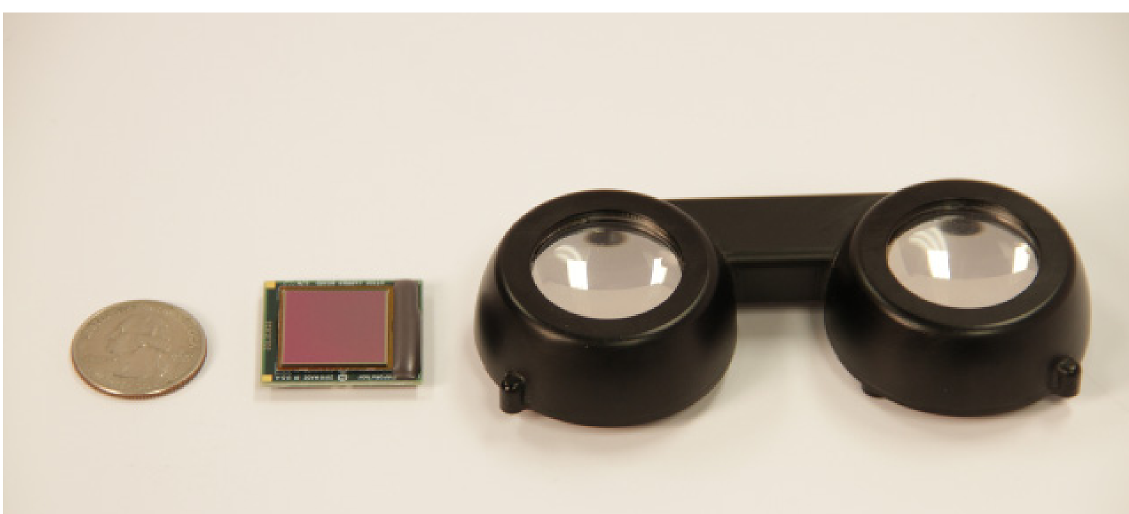

Figure 10: Pancake Optics next to the Lightning OLED Panel and a Quarter

Figure 9 shows the size of these optical modules in comparison to the Samsung GearVR headset, while Figure 10 shows the size of the pancake optics relative to the OLED panel and a quarter. It is very clear that the compact size of the Kopin OLED and optics allows much more stylish and comfortable VR headset designs.

The Pantile design is based upon hybrid Fresnel optics whereas the Pancake design uses conventional optical elements, but very tightly packed together. As Table 2 suggests, the Pancake design is thinner than the Pantile design with higher image quality, but the current Field of View is smaller as well as lower optical efficiency.

VR Design Solutions

Today, there are two basic classes of VR headset design: smartphone-inserted and PC-tethered. The smartphone-inserted category allows the user to place their own smartphone into the headset such as the Samsung GearVR device. This approach is attractive as the entry cost can be quite low - from free to a few hundred dollars. But the image quality and capabilities of the VR experience are determined by the smartphone. The PC-tethered category includes the Oculus CV1, Sony PlayStationVR and the HTC Vive.

Kopin sees two new categories of VR headset emerging: a smartphone-tethered solution and an all-in-one solution. Kopin's compact displays and optics are especially well suited for these categories of VR headsets by making them mobile.

PC-Tethered VR

PC-tethered VR headsets are generally viewed as the highest performance, the highest price and need to be coupled to the high performance PC. They are also viewed as having unfavorable ergonomics being big, heavy and clunky. The combination of headset, PC and accessories can easily cost $1,500 to $2,000 putting it out of the mainstream for consumer adoption.

The Pancake and Pantile optical modules from Kopin, coupled to their 2Kx2K OLED display, offers benefits and trade-offs for this class of VR headset. Table 3 shows a comparison of the optical modules from the VR headsets by Oculus, Sony and HTC compared to optical modules using the 2Kx2K OLED with Pancake and two versions of the Pantile optics.

This comparison illustrates well the trade-off between field of view, resolution, pixel per degree and size. If resolution is the same, increasing the field of view will decrease the pixel per degree. This will make any pixel structure more visible (screen door effect) and is likely to degrade image quality overall as more optical artifacts will become apparent in wider field of view designs – unless more complex, bulky and expensive optics are used.

The trend in VR headset design is to offer increasingly wider field of view headsets, but this may not be the right trend unless resolutions increase dramatically and optical cost-performance improves markedly. The other consideration is the size and weight of the headset.

The Pantile, and especially the Pancake optical designs, focus on optimizing the pixels per degree, but do sacrifice some field of view. Although a new Pancake optics with a substantially bigger FOV is being designed, a smaller FOV is a general characteristic of a microdisplay-based design compared to a direct-view design. The latter offer bigger FOV and lower PPD while the former optimize the other way. However, it should be noted that these Pancake and Pantile designs represent advancements in the state-of-the-art, offering a much more compact and viable solution for VR applications.

Such capabilities also beg the question: do all VR applications need ultrawide fields of view? Clearly the goal of a VR experience is to create a feeling of immersion and a sense of presence. But FOV is just one component of this emotional equation. One can argue, for example, that high PPD/moderate FOV coupled with precise 3D audio might be even more effective than moderate PPD/wide FOV. Of course content and many other factors all impact immersiveness and a sense of presence as well.

Comparison of Pancake and Pantile Optics with 2Kx2K OLED Microdisplay vs. CV1, PSVR and Vive					
	Pancake	**Pantile**	**HTC Vive**	**Oculus CV1**	**PlayStation VR**
Field of View	49 (H,V) 70 (Diag)	57 (H,V) 80 (Diag) 64 (H,V) 90 (Diag)	100Hx110V; 145 (diag) at 10mm eye relief	80Hx90V; 120 (diag) at 10mm eye releife	~100 H?
Display Size (diagonal)	.99" x 2	.99" x 2	~3.6" x 2	~3.6" x 2	~5.7"
Display Type	Kopin OLED on Silicon	Kopin OLED on Silicon	Samsung Pentile OLED	Samsung Pentile OLED	Sony OLED
Resolution per eye	2048x2048	2048x2048	1200x1080	1200x1080	960x1080
Pixel per degree (horizontal)	42	36 32	10.8	13.5	9.6
Visual acuity	20/40	20/40	20/80	20/80	20/80
MTF	not measured	not measured	not measured	not measured	not measured
Mura	compensated for	compensated for	compensated for??	compensated for??	compensated for??
Flare	not noticable	some noticable	some noticable	some noticable	some noticable
Crespuscular Rays	not measured	not measured	not measured	not measured	not measured
Screen Door Effect	Not noticable	Not noticable	Noticable	Noticable	Noticable
Distortions and aberrations	Not noticable	some noticable	some noticable	some noticable	some noticable
Frame rate	120 fps	120 fps	90 fps	90 fps	90, 120 fps
Color gamut	70% sRGB going to 100%	70% sRGB going to 100%	not measured	not measured	not measured
Luminance to the eye	20 nits going to 30+	50 nits	not measured	not measured	not measured
Display-Optics Thickness	<20mm	<30mm	>50-60mm?	>50-60mm?	>50-60mm?
Interpupliary adjustment	Possible	Possible	yes	yes	yes
Eye Relief	17mm	15mm	adjustable, 10mm optimal	adjustable, 10mm optimal	?
Eye box	> 10mm	>8mm	not measured	not measured	not measured
Focus adjustment	?	?	?	?	?

Table 3: Comparison of PC-tethered VR Headsets

Note that all of the VR headsets in Table 3 are based upon OLED technology, which has a very fast response time, fast refresh rates and less motion blur than LCD-based solutions. But the Pancake and Pantile designs use two OLED microdisplays compared to one or two direct-view OLED panels in the other headsets. The microdisplay solution allows for integration of display drivers on the display silicon, reducing the solution footprint, lowering display power consumption and improving reliability (fewer connections).

Currently, the Kopin OLED panels have lower luminance and color gamut than desired, but these are expected to reach their target values for VR products that can launch in Q4'17.

In terms of the Pancake and Pantile optics, both offer a larger eye relief than that offered by the others in Table 3, allowing the use of consumer eyewear, and probably a bigger eyebox as well. The Pancake design has great optical qualities, but is not optically efficient, meaning the luminance is a bit low today. This is expected to increase over the next 6 months via increases in the panel luminance and improvements to the optics.

The Pantile design has two versions with slightly different designs, manufacturing processes and field of views. These will be further evaluated in 2017 allowing products by the end of 2017.

Smartphone-Tethered VR

This is an emerging hybrid category with one product representing the category so far – The LG 360 VR. The idea is to focus on using the consumer's smartphone in combination with a lower-cost VR headset.

The LG VR 360 contains two 1.88" IPS LCD displays with 920x720 resolution per eye (639 ppi). The optics then create a horizontal FOV of 80 degrees and vertical FOV of 63 degrees. Also included in the headset is a 6-axis gyro and accelerometer and a headphone jack. Connected to the headset over a USB cable (USB 2.0 and Type-C supported) is the LG G5 smartphone.

Figure 11: LG 360 VR Headset Optics

The big advantage of separating the processing and communication power of the smartphone from the headset is that the headset becomes considerably smaller and lighter compared to PC-tethered to smartphone-integrated headset designs (see Figure 12Figure 12). The LG 360 VR comes in at 116 grams vs. the 345 grams for the Gear VR – plus the weight of the smartphone.

LG appears to have taken the design approach that is not truly immersive, however. That is, the soft grey foam that sits between the headset and the user's face does not entirely block out light or even vision. One can see in up/down and left/right, which breaks the immersive illusion of VR. But it is also apparently necessary as the interface to the headset is the smartphone, which can be manipulated by the user by rolling your eyes downward to see the phone's display. Reviews of the headset have not been too favorable so far citing the light leakage, control awkwardness, poor motion-to-photon latency and lack of resolution improvement over competitive devices.

Figure 12: LG 360VR vs. Samsung Gear VR

These criticisms indeed seem fair, but they can be addressed. Clearly a headset design using the 2Kx2K OLED panels with the Pancake or Pantile optics would offer an even smaller form factor with a significant resolution increase with around the same field of view (leading to much higher pixels per degree).

A better user interface is desirable too. A touch pad on the side of the headset is doable now. Voice or eye activation is also possible, but may not be mature enough yet for full functionality. This should happen within the next year or two, we suspect. Hand and arm gesture will also be a key part on this new user interface paradigm. The lack of immersiveness can be handled once the improved user interface is introduced allowing for face-hugging and light-blocking materials to be used.

The large motion-to-photon latency of LG 360VR is both due to a display issue (slower response time and slower frame rate of the LCD panels) and an electronics issue that can be related to the sensor processing, delays in transmitting this data back to the smartphone, processing delays on the phone, and transmission delays back to the headset, plus the display time delay. We suspect this pipeline has not been optimized for this architecture due to the limitation of the processor speed, which again, is likely a solvable problem within a year or two.

Many new smartphone are now offering the USB connector with DisplayPort 1.4 Alt C compatibility. This wired interface offers 32 Gbps over four lanes offering developers both a high bandwidth display path and a 10 Gbit Ethernet data channel as well. This should help with latency issues in an optimized pipeline architecture.

It may also be possible to consider a wireless link between smartphone and headset. Wifi may be able to carry the video with Bluetooth providing a back channel for the 6-axis orientation data.

As these design concepts evolve, we would anticipate that different teams will make alternative design choices regarding what aspects of the pipeline and components to leverage from the smartphone or locate in the headset. For example, tracking sensors, microphone and speakers (or speaker jack) will need to be in the headset as well as 6 degree of freedom inertial sensors, but maybe other components should be there as well. Maybe is it possible to offload some sensor processing to a CPU located in the headset or even locating GPU cores there to speed up display rendering? Such analysis of the trade offs in locating functionality in the smartphone or in the headset will need to be undertaken to understand the performance, ergonomic and economic impacts on the system design.

We expect more optimized products to appear in 2017 and 2018.

All-in-One VR

Perhaps by Q4’17, but certainly in 2018, we expect to see the introduction of all-in-one VR headset designs. The idea is to offer a fully untethered mobile solution with all of the functionality in the headset. What designers would like to do here is to replicate the high end PC-tethered experience without the need to buy and connect to a high-end PC. These can be very useful for consumers, but especially for public entertainment venues for VR experiences.

In the Augmented Reality segment, the Hololens and the ODG R8 and R9 headsets are examples of all-in-one concepts. In the virtual reality realm, we have seen all-in-one concepts from Intel and Qualcomm.

In addition, VR Arcades or VR experience centers are starting to roll out the all-in-one VR headsets too. These are room-scale experiences where participant don backpacks with PCs, headgear and accessories for 5-10 minute adventures in VR. IMAX and The VOID and others have already rolled out such solutions.

Fully-Integrated VR Headsets

Intel's Project Alloy and Qualcomm's VR820 (and newly announced VR835) are examples of fully-integrated VR Headsets. That means all of the communication, processing, cameras, sensors, display and batteries are part of the VR headset. Both include 3D sensing solutions to create a 3D model of the room along with a visible camera so virtual objects can be mapped to real objects. As a result, one might even consider this a mixed or merged reality experience since it includes a real world environment.

This virtual world can now serve as the backdrop for travel, sports, games and other entertainment uses. Intel also showed hand controls to augment the game play. For example, a real tabletop can transform to a virtual chessboard with virtual pieces. The walls can became sky and furniture became different objects in the game. Bookshelves can turn into rusty pipes. Multiple players can exist in this environment, seeing and interacting with each other.

Figure 13: Intel's Project Alloy VR Headset

Project Alloy was announced in August 2016 and a prototype was shown privately at CES 2017. It is a reference design the company is offering partners who can then make their own commercial headsets. Figure 13 shows the Project Alloy headset. No details on any of the hardware specifications have been released, but it clearly resembles conventional headset designs with a large battery in the back.

Figure 14 shows the Qualcomm VR820. Like Project Alloy, this is a reference platform to entice developers to use the Qualcomm Snapdragon 820 SoC along with its VR Software Development Kit. Included in the VR820 are integrated eye tracking for two cameras, motion-to-photon latency of less than 18 ms, dual front-facing cameras (one for images and one for depth sensing) for 6 degree of freedom and see through applications, four microphones, gyro and accelerometer and magnetometer sensors.

Figure 14: Qualcomm VR820 Reference Platform

The headset was first shown behind closed doors at IFA 2016 and was built by Goertek. This version integrated an Adreno 530 GPU for smooth graphics, foveated rendering using an OLED panel with 1440 x 1440 resolution per eye and supporting 70Hz refresh. The system can play back 360º UltraHD HEVC video at 70 fps. Included in the VR820 are integrated eye tracking, motion-to-photon latency of less than 18 ms, dual front-facing cameras (one for images and one for depth sensing), four microphones, gyro and accelerometer and magnetometer sensors.

At Mobile World Congress 2017, Qualcomm unveiled the Snapdragon 835 mobile SoC and a new VR reference headset using this device and their VR SDK. The VR headset includes a single OLED panel with total resolution of 2560x1440 (WQHD) resulting in about 2 megapixels per eye. 6DoF sensors and tracking plus the two cameras from the previous platform are retained. The Snapdragon 835 VRDK's head mounted display packs 4GB of LPDDR4 RAM and in terms of connectivity options, it offers Wi-Fi, Bluetooth, and USB 3.1 type C. There is also a trackpad located on the right side of the VR headset. It will be available in Q2'17.

Qualcomm also announced a head mounted display accelerator program, which allows manufacturers to build their own head mounted displays from the reference designs or receive help from turnkey original design manufacturers like Goertek or Thundercomm to modify the Snapdragon 835 powered headset to suit their requirements.

Clearly, size, weight, power, ergonomics, visual performance and more are all critical elements of this type of all-in-one VR headset design. An OLED microdisplay solution seems best suited to meet this need.

<u>Location-based VR</u>

All-in-one VR solutions are being fielded today, but not in the form factors envisioned by Intel and Qualcomm as described above. Instead, developers are using existing PC-tethered type VR headsets and placing a compact PC in a backpack that the user wears. Additional haptic devices are instrumented in the vest along with accessories that transform into blasters or other devices for use in the VR experience. This is a VR Arcade type experience.

Figure 15: Ghostbusters VR Experience by The Void

For example, in July 2016, The Void teamed up with Sony Pictures to create a VR experience around the release of the Ghost Busters movie. This was not a VR trailer intended to be viewed at home, but a multi-user experience that was created at the Madame Tussauds wax museum in Times Square in New York.

The idea is to allow a group of customers to don VR headsets, backpacks and mock proton guns, then immerse themselves in a virtual ghost busting adventure. The experience features travel thru several rooms before players arrive at the VR area, so it's really a theme park-like environment.

The experience is multi-player (3) so players can see avatars of their friends and have conversations with them as they blast ghosts. There is room to move around in a dedicated play space which includes real opening doors and real chairs to allow sitting in the virtual environment. Players can even feel ghosts passing through their body or the impact of a blast, thanks to localized haptic feedback in the vests worn by each 'buster'. Plus, the experience includes full body tracking of motion through rooms and an elevator ride.

Clearly, this level of entertainment is not possible in the home. Yet, it uses Oculus CV1 headset with a Leap Motion module to track hand movements. Rumble packs on the vest provide haptic inputs while the backpack has the computer ad battery pack.

In addition, IMAX has now opened their first of a series of planned VR adventure centers in Los Angeles. It is similar in concept to the Zone solution offering customers the chance to experience several different short VR adventures.

Figure 16: IMAX VR Adventures

Instead of the Oculus headset, IMAX chooses to use both the HTC Vive headset and the Starbreeze StarVR headset, which offers the widest 210-degree field of view. As we now know, the wider the field of view the more likely the pixels will be visible along with other artifacts like the screen door effect. And indeed, this has been one of the principle complaints of the system.

It is a multi-player solution where participants can wander from "pod" to "pod" where a backpack and vest with PC and haptics, along with accessories, like weapons. Player movements are tracked allowing for player interaction. There are 14 pods in the LA location.

Other groups are establishing similar centers worldwide. For example, Bandai Namco Entertainment has launched the VR Zone Project i Can in the Divercity Tokyo Plaza shopping complex. Sega Live Creation has created a VR experience in its Tokyo Joypolis amusement center, with an eye toward expanding the experience to other Joypolis facilities across Japan and China. And, MK2 is working on a center Paris. These are just some of the activities.

This category of all-in-one VR appears to be getting a lot of attention – and money. By combining all of the technology elements to create an adventure that is not possible in the home, these venues are serving as a great way to introduce the public to VR and all it can offer. It is a pay-as-you-go approach that does not require any investment for the consumer and represents a large opportunity for suppliers as well.

Untethered all-in-one VR is the most challenging design as one needs to add the high-end PC to the already crowded and bulky headset design. However, it is clear that the latest SoC designs, especially ones for mobile applications, are now being tailored to support the VR pipeline. This includes optimizing the pipeline to minimize motion-to-photon latency and even parallelizing GPU display rendering tasks. Designers will have to be creative in distributing components around the headset to make for good ergonomic designs, but it is still likely to feel more like a helmet than a headset.

OLED microdisplay headset solutions seem very well suited to meet the needs of this market: smaller size, weight, and power as well as higher performance. But success here is clearly more than just the capabilities of the Kopin OLED panel and optical modules, and it will take time. Nevertheless, the availability of higher performance OLED microdisplays and compact optics are a big step in this direction.

Conclusion

This white paper has provided a comprehensive analysis of the design factors that influence the final VR headset design. These factors are many and are tightly interweaved making trade-off analysis a complex and difficult process.

We have also analyzed several current direct-view headset designs and compared with new OLED microdisplay designs. This analysis suggests that current VR headsets do not meet the key image performance desires of end users, nor the size, weight and comfort issues either. If VR is to become a mainstream product, VR headset makers must radically improve design and performance. One question is whether all VR applications need ultrawide fields of view. Clearly the goal of a VR experience is to create a feeling of immersion and a sense of presence. But FOV is just one component of this emotional equation. One can argue, for example, that high PPD/moderate FOV coupled with precise 3D audio might be even more effective than moderate

PPD/wide FOV. Of course content and many other factors all impact immersiveness and a sense of presence as well.

We have also explored the various sub-categories of VR headset architecture including PC-tethered, smartphone-inserted, smartphone-tethered and all-in-one designs. While smartphone-inserted designs are the most popular today, their performance is also the lowest quality.

PC-tethered and the location-based all-in-one designs offer the best VR experiences today, but with trade-offs. The PC-tethered designs have mediocre image performance, poor ergonomics, limited range and require an expensive investment by the end user. Location-based all-in-one VR is more like an amusement entertainment experience. It requires travel and has similar image performance and ergonomics issues as the PC-tethered, but with a different business model (pay per ride).

The smartphone-tethered category offers an interesting hybrid approach that has yet to be explored by many players, but seems ripe for exploitation.

The bottom line is that VR headset image performance, ergonomics and pricing need to improve dramatically to satisfy the needs of end users. The new 2Kx2K OLED panel from Kopin, along with their Pancake and Pantile optics are a clear improvement in image quality as well as smaller optical form factor. This can form the basis for higher fidelity, smaller, lighter and better fitting VR headsets in the near future. And, Kopin has a 3Kx3K OLED panel on the roadmap as well, offering a path to continuing improvement.