Zemax

ENVISION2021

Optical design of a compact AR system based on the pancake lens

David Kessler

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Kessler Optics & Photonics Solutions. Ltd.

- 24 years at Kodak Research Labs running an optical design team
- After Kodak started KOPs in 2006   www.KesslerOptics.com
- Using Zemax extensively
- 99 granted US patents
- Design for and consulted so far to 20   AR/VR companies.

Agenda

- AR/VR Customers -initial requirements
- Choice of architecture
- Artifacts !
- A design example for a bird bath 60^0 FOV
- The design of a pancake based AR
- Modeling issues
  - Merit functions
  - Modeling of wire grid elements
  - Conversion to non sequential

What does everyone want? (2013)

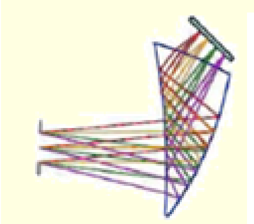
Oakley Thump =
Sunglasses+MP3

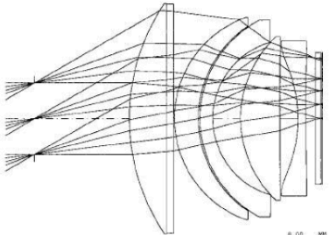
"Oakley look" .	i.e., thin & small optics
Augmented imaging	preferably an optical see-through channel
Low cost	& small image generators (OLED, LCOS, micro-LEDs...)
Wide field of view	30^0 deg to 110^0 full diagonal field
Large eye box	~10 mm diameter, for eyeball movement + loose alignment
Large eye relief	> 20 mm, for lash clearance and prescription glasses
High resolution	~ SXGA (1280 x 1024) or higher
Low distortion	< 2%
Bright	hundreds of Cd/m^2 indoors, thousands outdoors
Artifact free;	no "dirty windows" ; no raster; no sunlight scattering; no color shading; no interference fringes et.
Low weight	
Other:	eye tracking; battery life; connectivity....

Bottom line: you can't get them all. Let's get the important ones and trade off on the others:

NEDs: categories of optical design forms (2013)

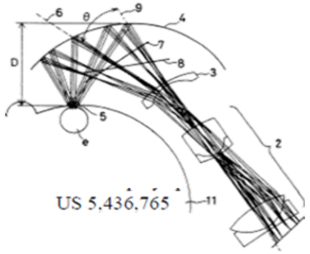
- Magnifiers i.e. eye piece + image generator

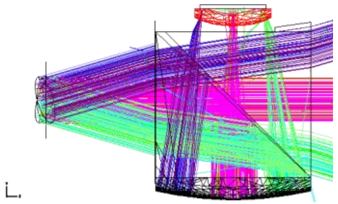




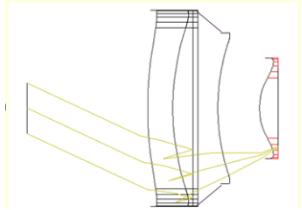
- Relay based NEDs

- Monocentric system

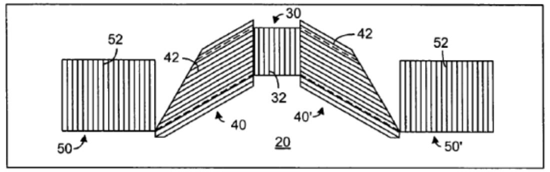




- “Pancake” designs : on axis folded by polarization means



- Pupil splitting :

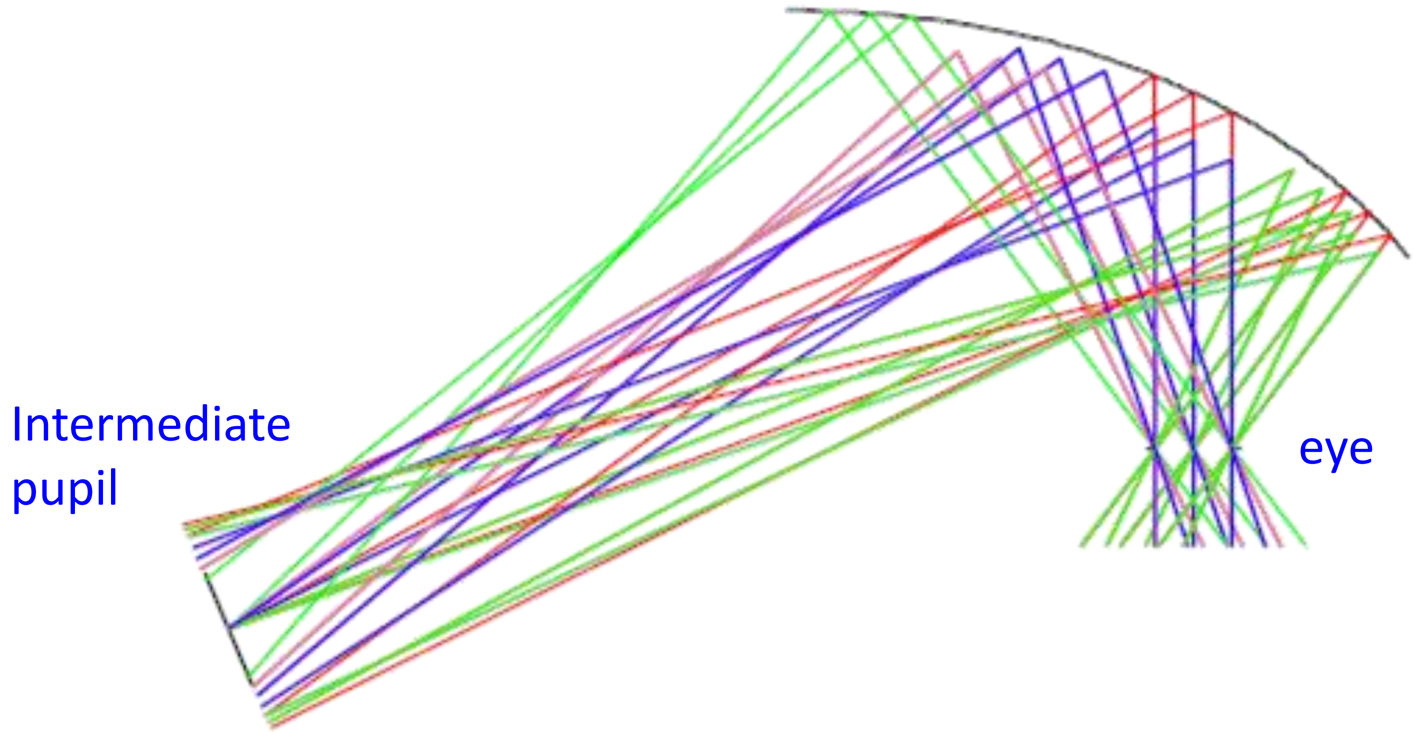


- Segmented (or tiled) NEDs:

- Other: Foveated; Fiber scanning; Retina scanners; etc.

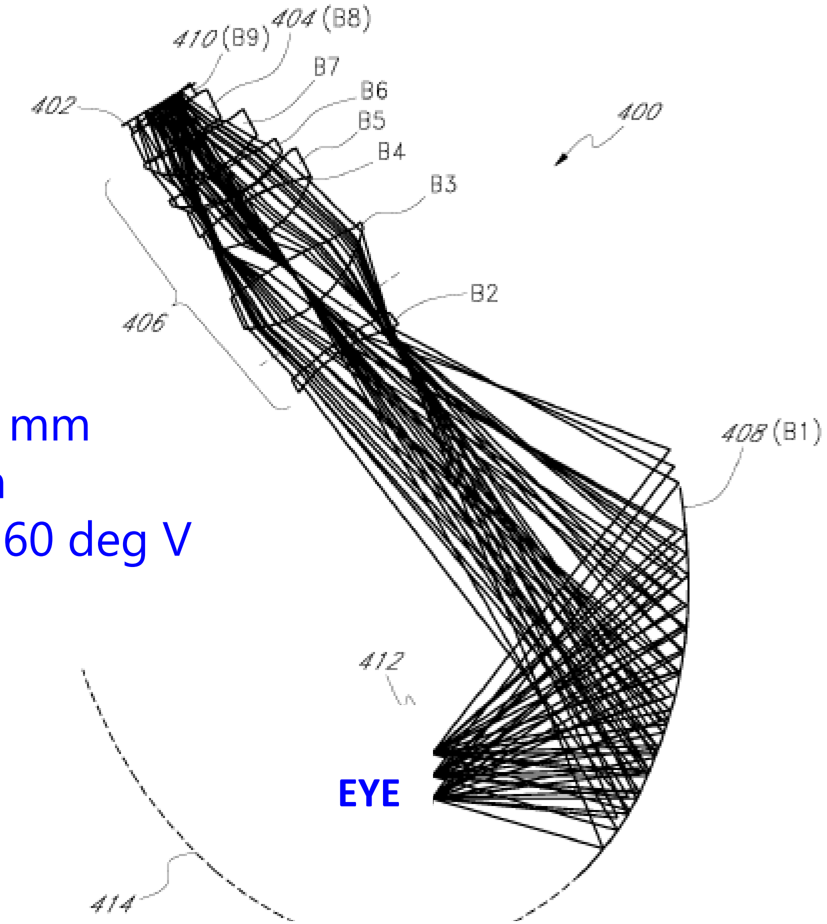
The core of the combiner design difficulty

The powered combiner such an ellipsoid can easily relay the **pupils centers** when their centers are at the ellipsoid foci. However, it cannot by itself **maintain the beam collimation** at its power changes over the field and the large off axis aberrations have to be corrected by the remaining optics.



Pilot training HMD using symmetrical elements

The designs are based on the “Nodal Theory” by Thompson and Shack which shows that the aberrations of the tilted combiner can be compensated by a system using tilted symmetrical components which does not result in new aberrations , but just adds new field dependencies.

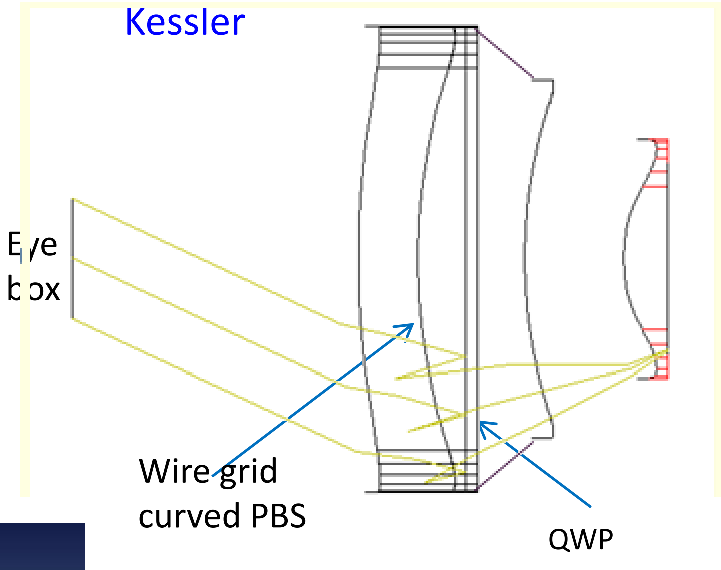


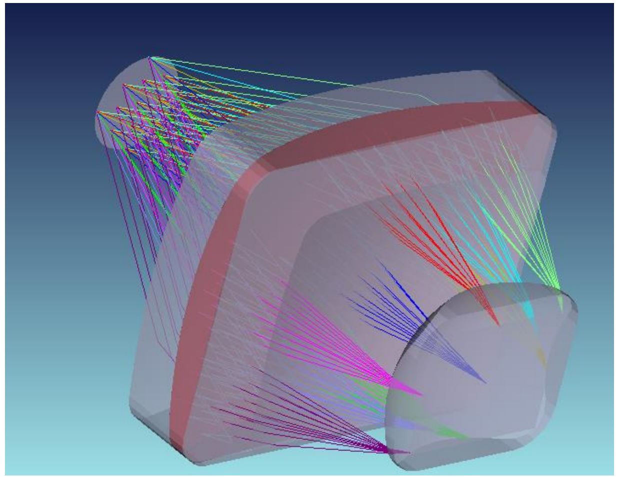
Eye Relief > 50 mm
Eye Box 15 mm
FOV 65 deg H, 60 deg V
SXGA

A. Sisodia, A. Riser, J.R. Rogers “Design of an Advanced Helmet Mounted Display “ Proc. SPIE Vol. 5801 (2005)

“Pancake “ NED designs- the importance of symmetry

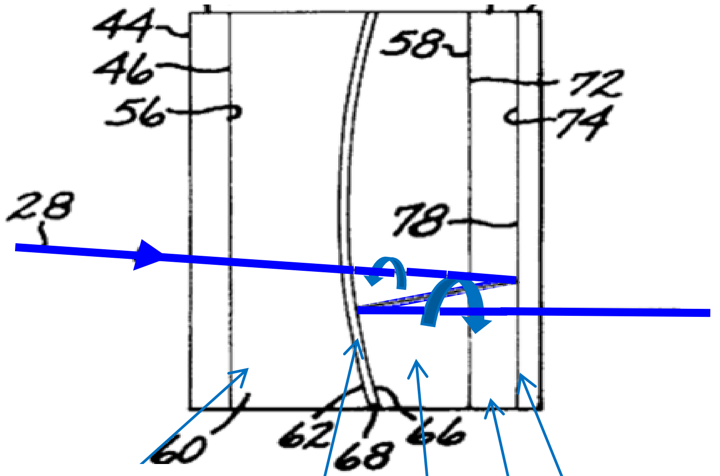
On axis designs folded by polarization means





SXGA
60^0 FOV
10mm Eye box
24 mm Eye Relief
problems : efficiency ~ 6% and usually not (optical) see through

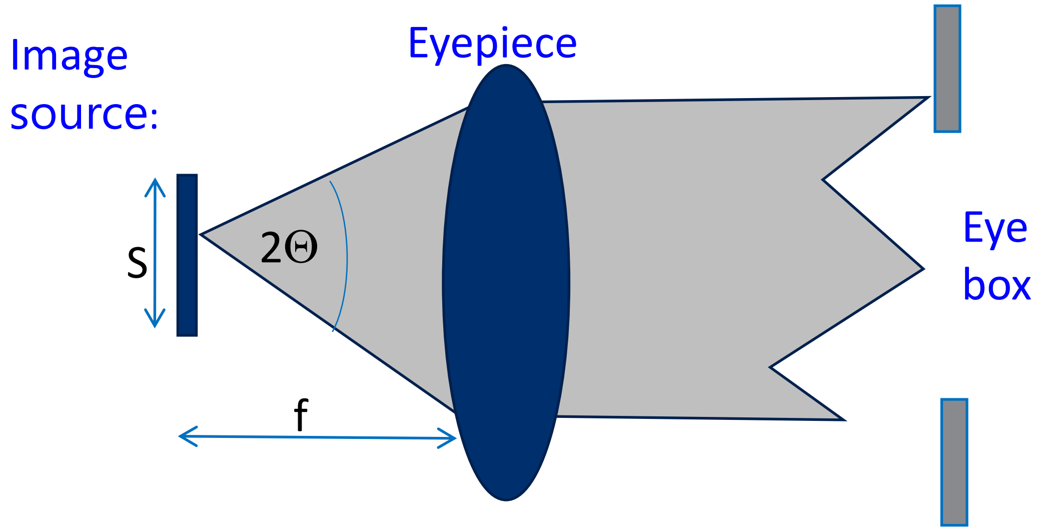
Raytheon US
6,563,638B2



Pupil splitting designs
(also: pupil expanders and dilated optics)

We want an optical system to project into the eye with :

* Low F/number (= high Numerical Aperture) for efficiency
* large eye box
* Short focal length for large field and small optics



NA = sin(θ)
(Eye Box) = 2*f * NA
FOV = S / f

However , short focal length means small eye box, so we use a short focal length and get a small exit pupil and then expand it by replication to fill the eye box.

Conservation laws and invariants

Etendue = $A\,\Omega$

where A = area

Ω = projected solid angle = $\pi * (NA)^2$

$P = B*A*\Omega$,

where P = power ,in lumens or Watts

B = luminance in Cd/m^2 or Nits

The three conversion laws (when there is no pupil expansion or diffusion)

$P' = P$	energy conservation
$A'\,\Omega' = A\,\Omega$	Etendue invariance,
$B' = B$	Brightness theorem

When we diffuse at the image or expand the pupil:

$P' = P$	energy conservation
$A'\,\Omega' > A\,\Omega$	Etendue is increased

$A' > A$ for pupil splitting or pupil expansion

$\Omega' > \Omega$ diffusion expansion at an intermediate image

$B' < B$ Brightness decreased

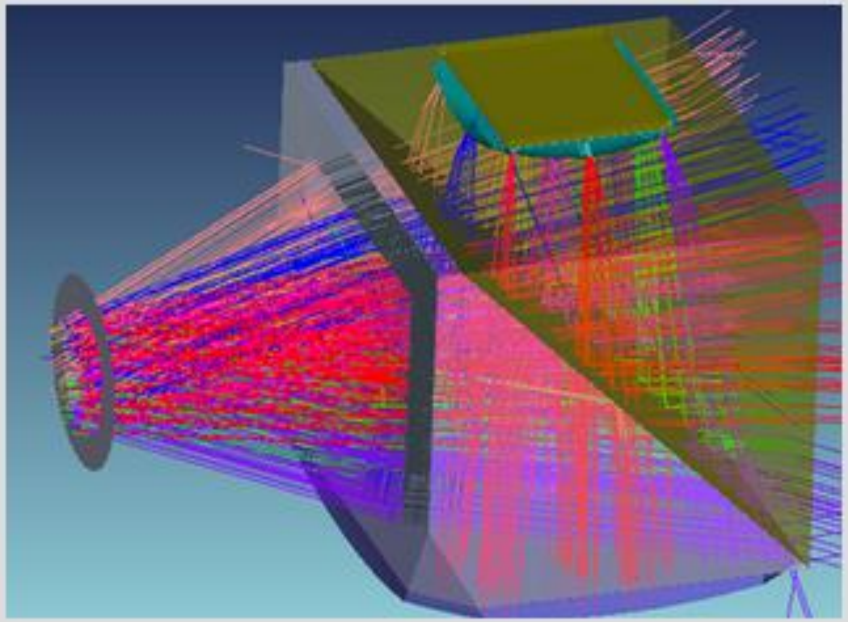
Image artifacts have to be considered in designs: The “Dirty windshield” artifact

Sunlight scattered off structures and discontinuities on the windshield or in the context of AR system- structures on the combiner.

The shimmering artifact

See-through: SXGA; 50^{0c}diagonal; 10 mm Eye Box ;23mm Eye Relief; 0.78" OLED

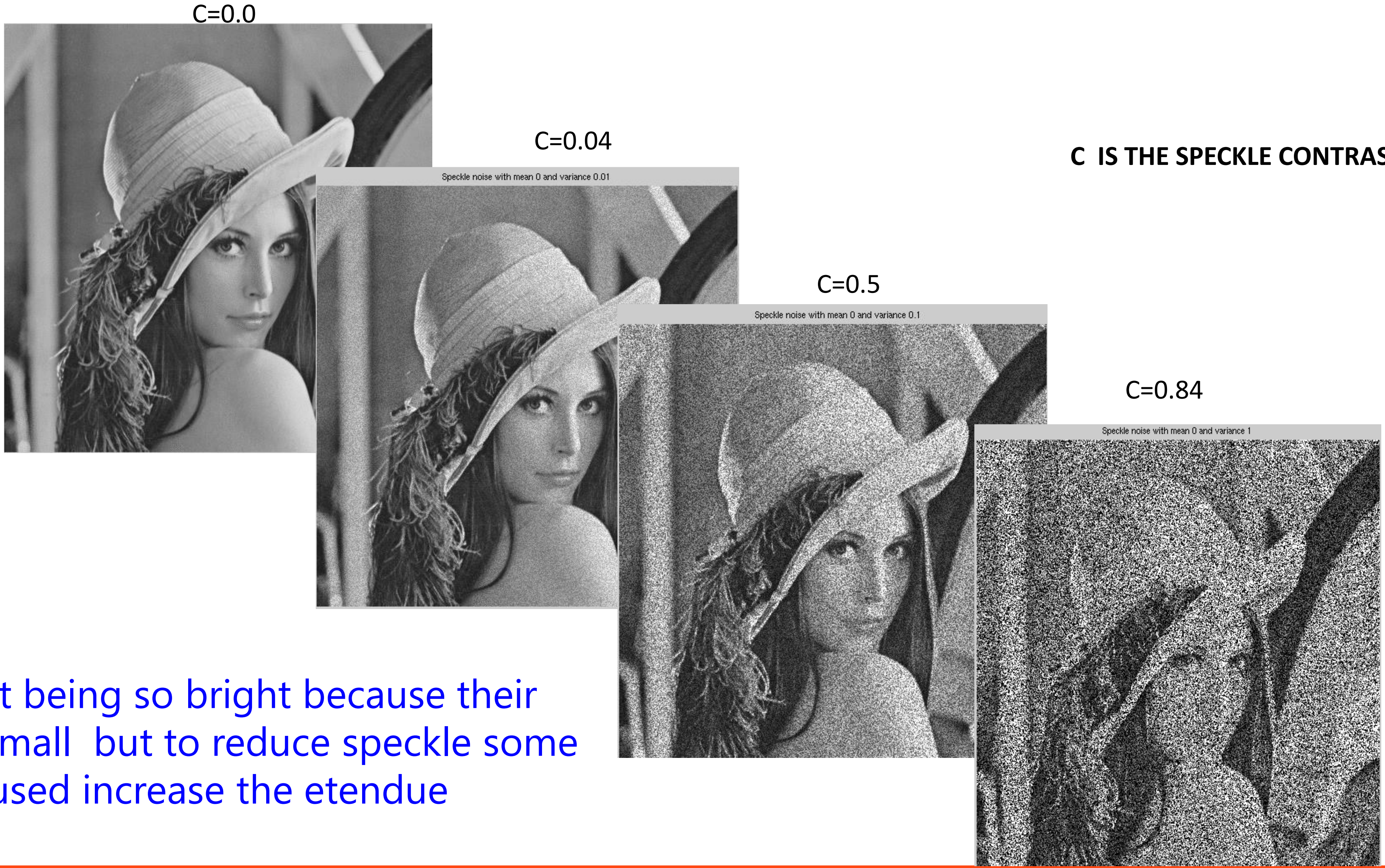
Kessler and Bablani , USA 8094377



<u>Two ways to design for low shimmering system:</u>

1. to optimize use the full eye box- may be an overkill since the eye is a sub aperture of the eye box at any given position.
2. To use multi configurations for the sub apertures at different location within the eyebox and include chief ray deviations in the merit function.

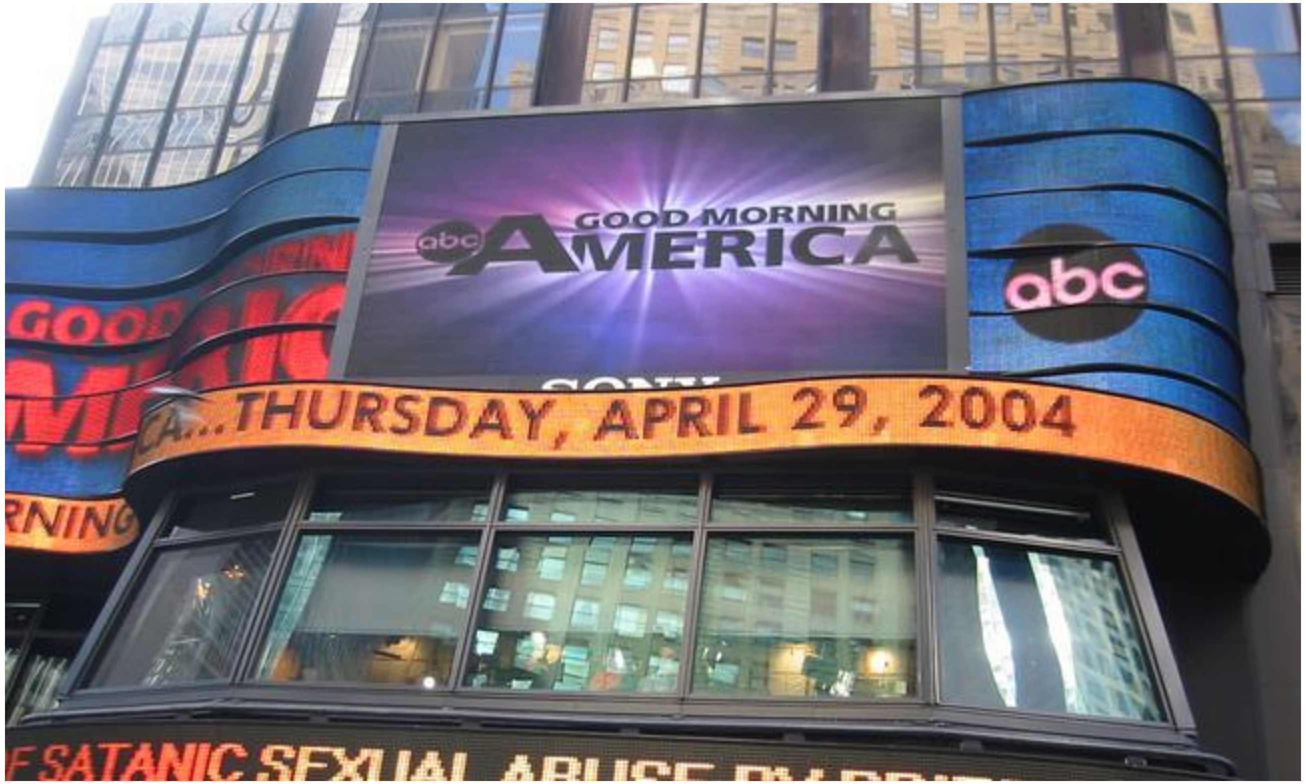
SPECKLE artifact

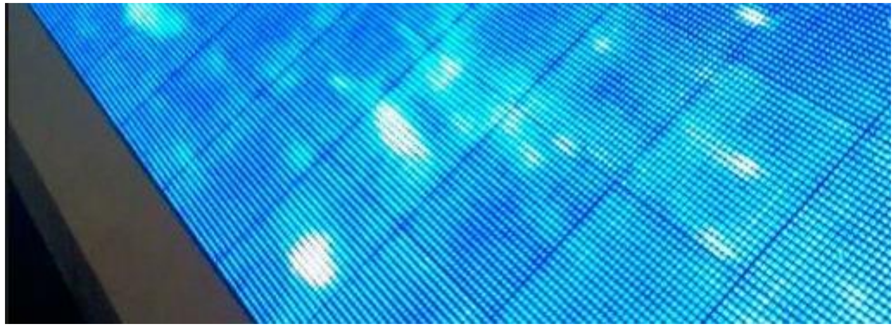


C IS THE SPECKLE CONTRAST

Lasers are great being so bright because their etendue is so small but to reduce speckle some of the means used increase the etendue

Tiling artifacts

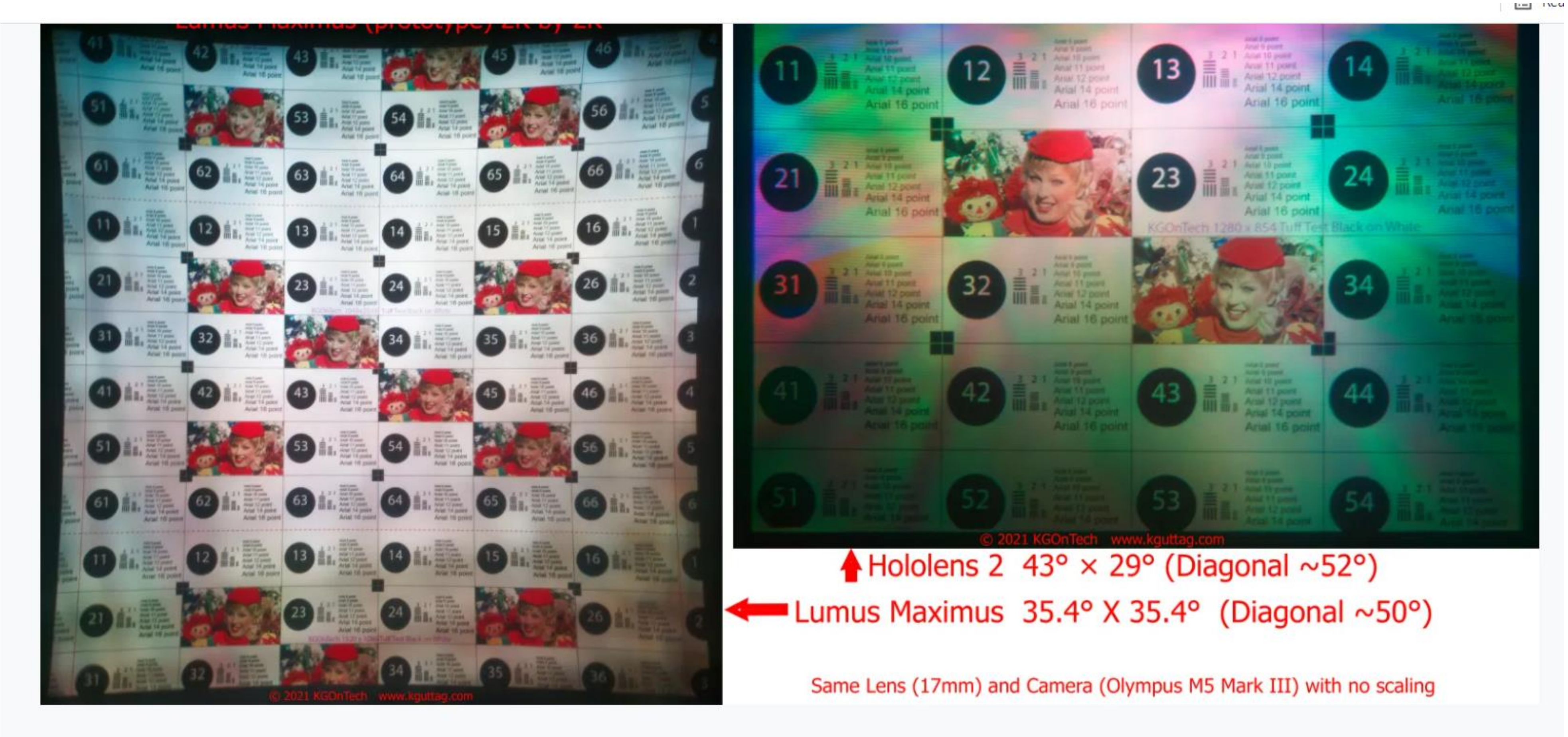




LED displays are usually assembled of 6” x 6“ modules
Concealing tiling artifacts for limited FOV is relatively easy. Concealing over the full FOV is not.

Color artifacts:

Latest shoot out between Lumus Maximus and Hololens II



From Karl Guttag blog- there are differences in resolution and field, but the color artifacts are quite noticeable on the Hololens II

A design example of Large FOV bird bath + relay configuration

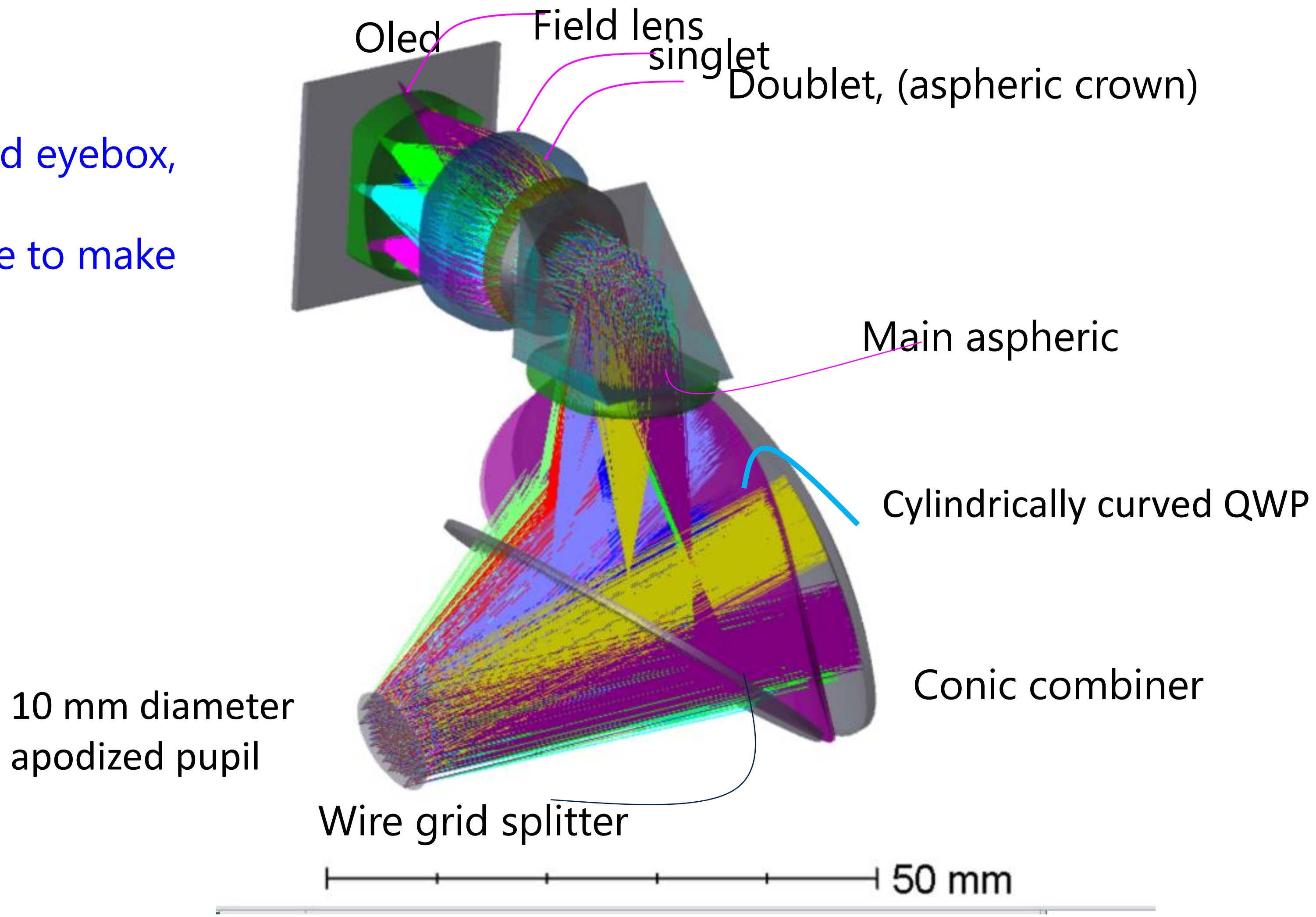
presented on the 6/9/2021 Zemax Summit event.

The main specifications for this design are:

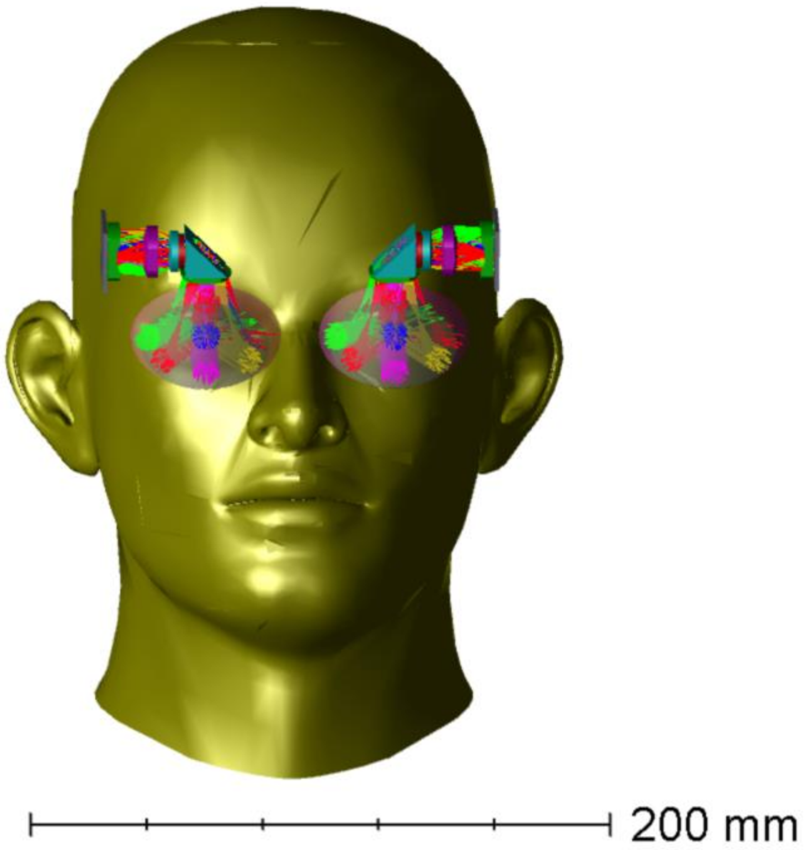
1. The field of view of 60^0 by 40^0 (70^0 diagonal)
2. The eyebox of 10 mm diameter
3. Eye relief (from the eye to the closest part of the splitter) > 20 mm
4. Resolution – need to resolve the 7.2 microns pixels of the OLED.
5. Maximize brightness in NITS using a customer chosen 3000 nits OLED.
6. No obscuration of the see through except for looking above the 40 degrees field since one application is for patients with macular degeneracy
7. Reduced components complexity (no free-forms at least initially) to allow relatively short build.
8. Reasonable esthetics- but some size flexibility there
9. Use the customer chosen 2560 x 2560 pixels OLED 3000 NITs

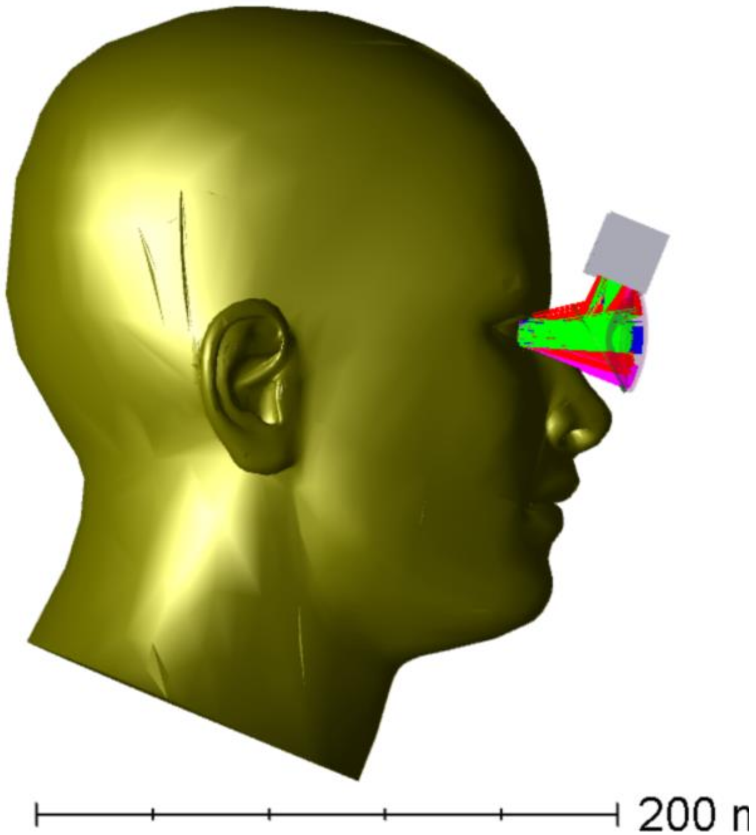
Bird-bath covered in the Zemax Summit 6/9/2021

10 mm gaussian apodised eyebox,
Conic combiner
Stop at prism hypotenuse to make the prism smaller.



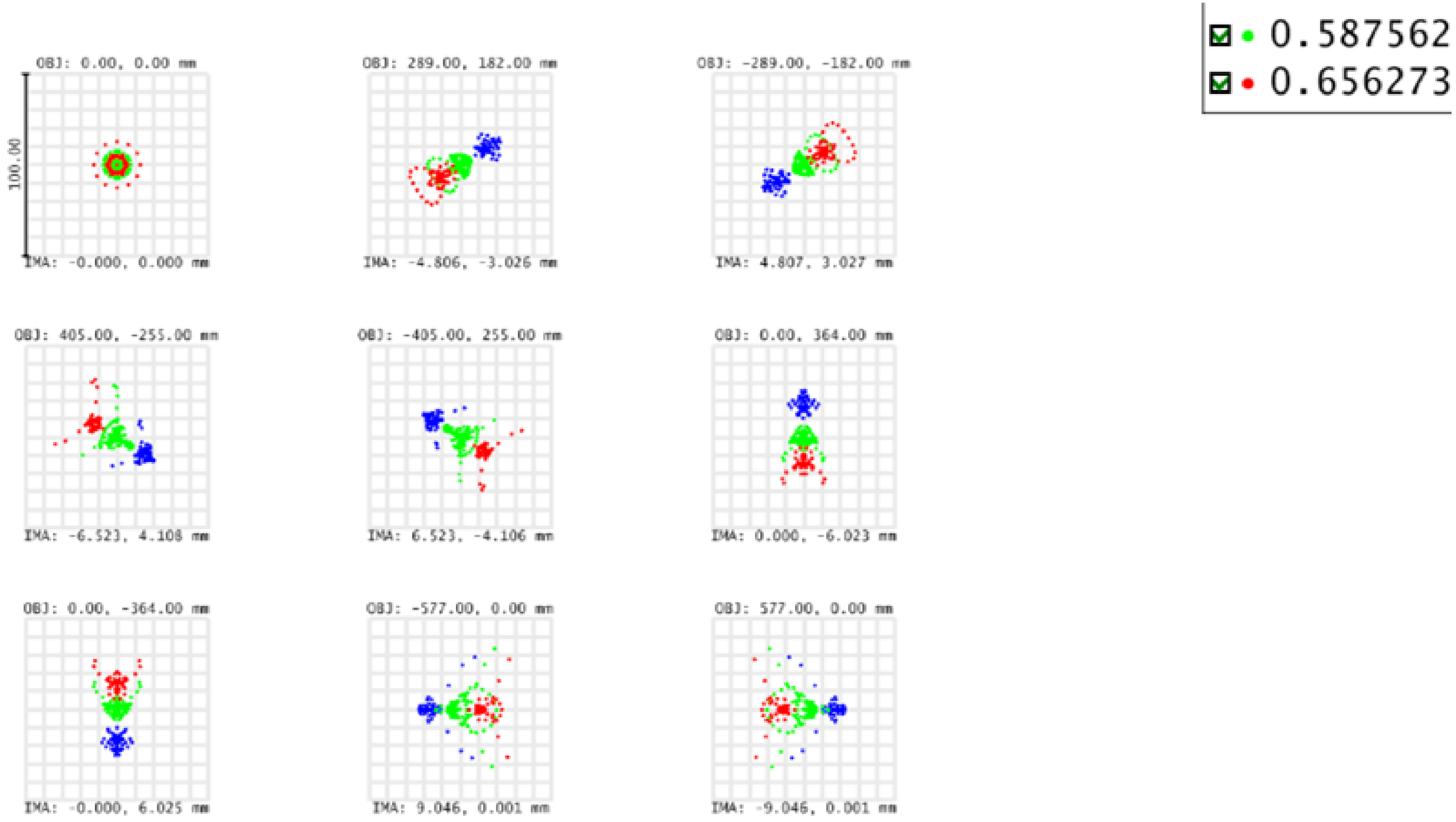
The final design shown on a head.





RMS spots and lateral color

Per color the spots are within the 7.2 μ of the OLED.
Lateral color can be digitally corrected



Surface: IMA

Spot Diagram

3/3/2020
Units are µm. Legend items refer to Wavelengths

Field :	1	2	3	4	5	6	7	8	9
RMS radius :	5.633	13.110	13.236	13.729	13.504	12.745	12.852	14.173	14.173
GEO radius :	12.722	28.482	29.103	34.203	33.909	27.600	29.360	38.538	38.538

Scale bar : 100 Reference : Centroid

Zemax
Zemax OpticStudio 16.5 SP4

SEQ_3_3_2020_GLOPT_HH_PREFERRED_variance_opt.zmx
Configuration 1 of 1

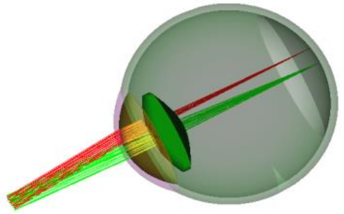
Shootout of the 60^0 x 40^0 birdbath Hololens II

Optical design of a **compact**, large-field AR system based on the pancake lens

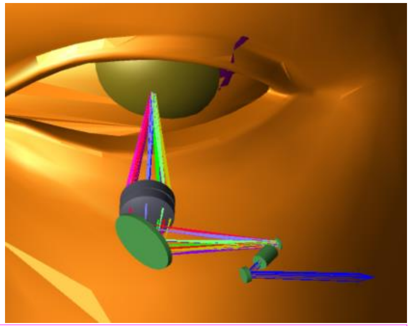
- Evolution of the design
- The requirements "negotiation" process
- Choice of architecture
- The design process- considerations ; issues encountered ; performance
- Non sequential design
- Interface with the mechanical designers
- Performance

The evolution of the Amalgamated Vision “see above “ system

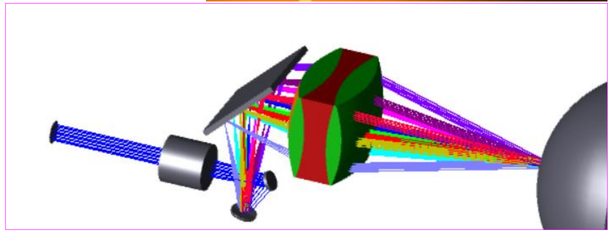
Initial requirement: no optics, just a close by scan mirror to be placed closer then 16 mm away where the augmented channel is not interfering with the see through and the prospective user- a surgeon will be looking down to see it.



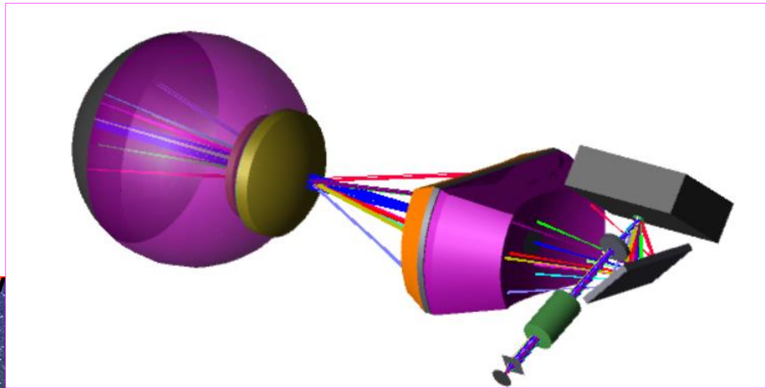
Adding a simple relay from the scan mirror to the eye to increase the field and prevent beam wondering on the iris. The eyebox is the size of the mirror about 1 mm with a 1:1 relay. The relay images the scan mirror onto the iris and collimates the beams focused on a curved focal surface in front of the relay.



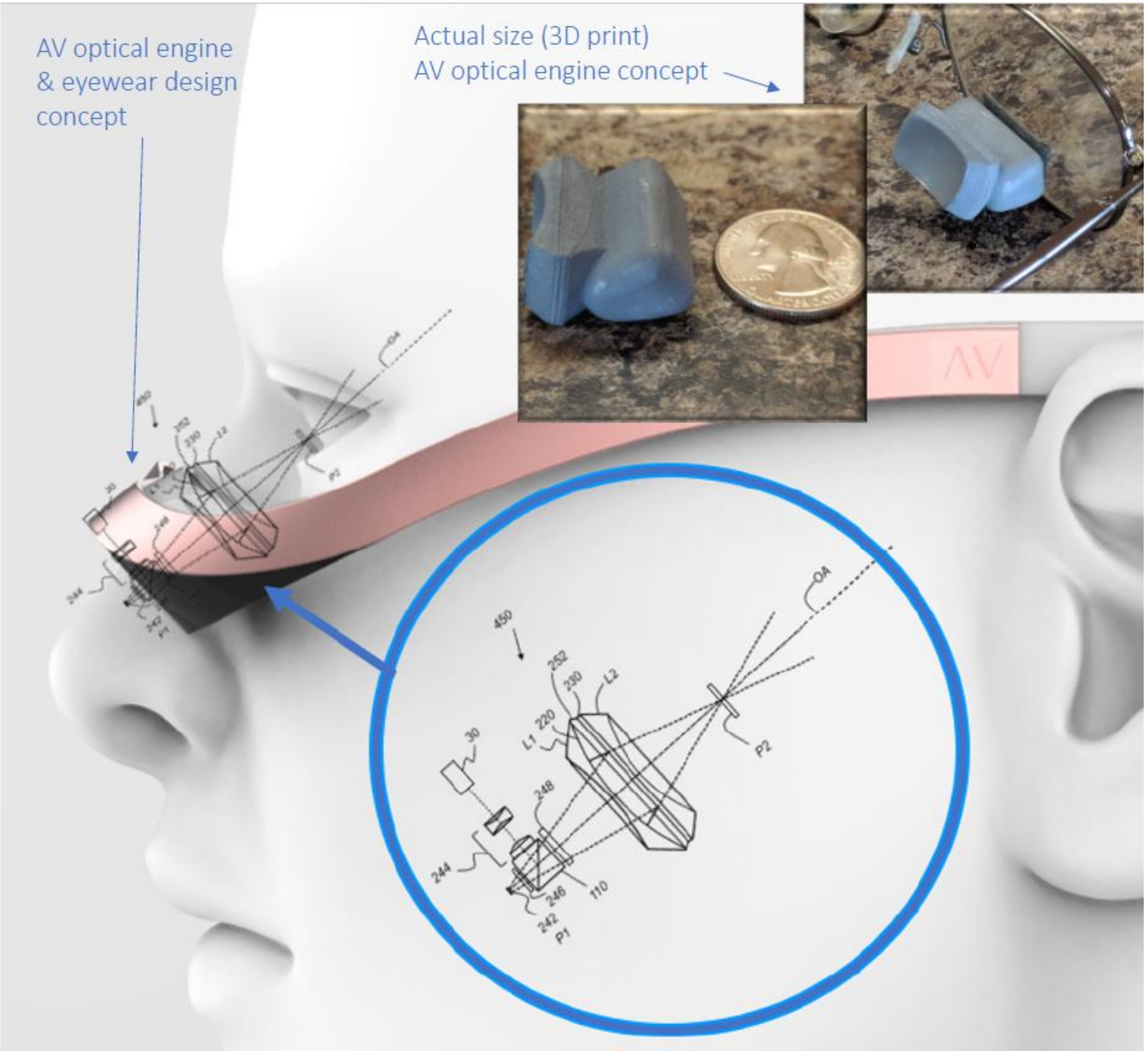
Using a Steinheil triplet with increased field to 24^0



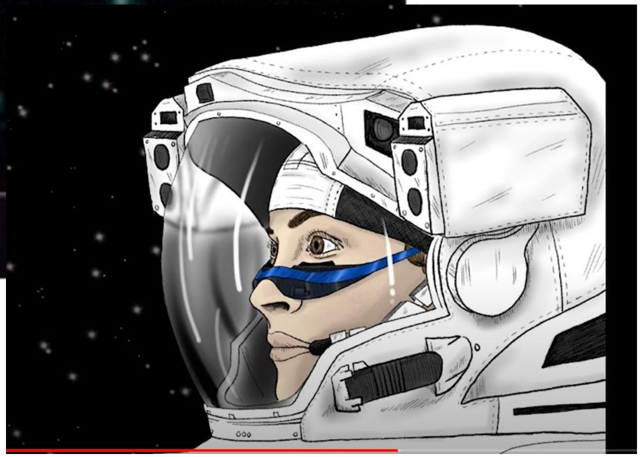
Changing the relay into a pancake lens and increasing the FOV to about 43^0 x 24^0. Still with a small eyebox. Later we will show how the eyebox was increased to about 8 mm diameter.



The system as presented by Amalgamated Vision
(https://www.amalgamatedvision.com/)

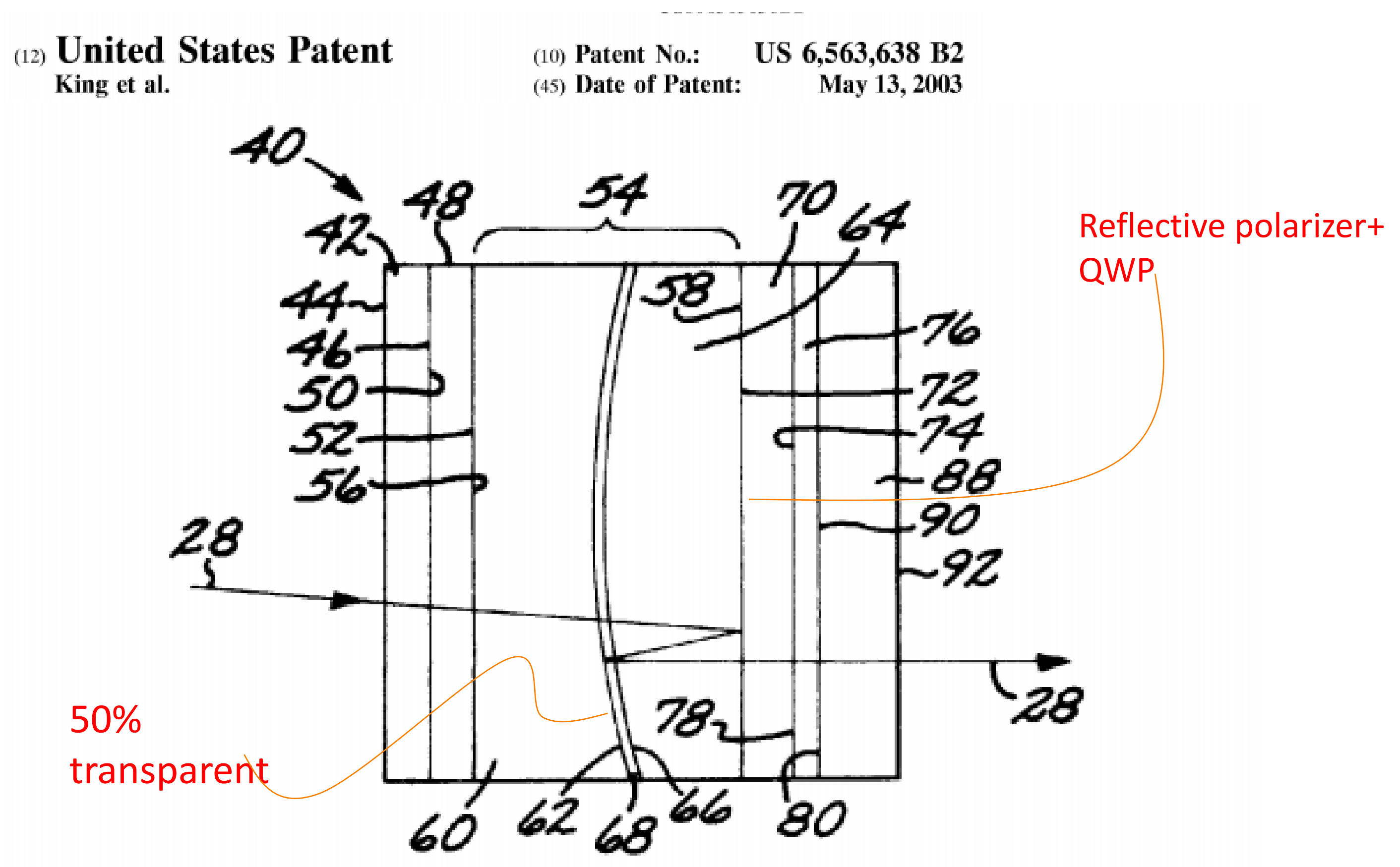



NASA iTech
2020 CYCLE I FORUM
OCTOBER 1-2 | VIRTUAL EVENT
CONGRATULATIONS WINNERS!
AMALGAMATED VISION | MOJO VISION | OTOLI



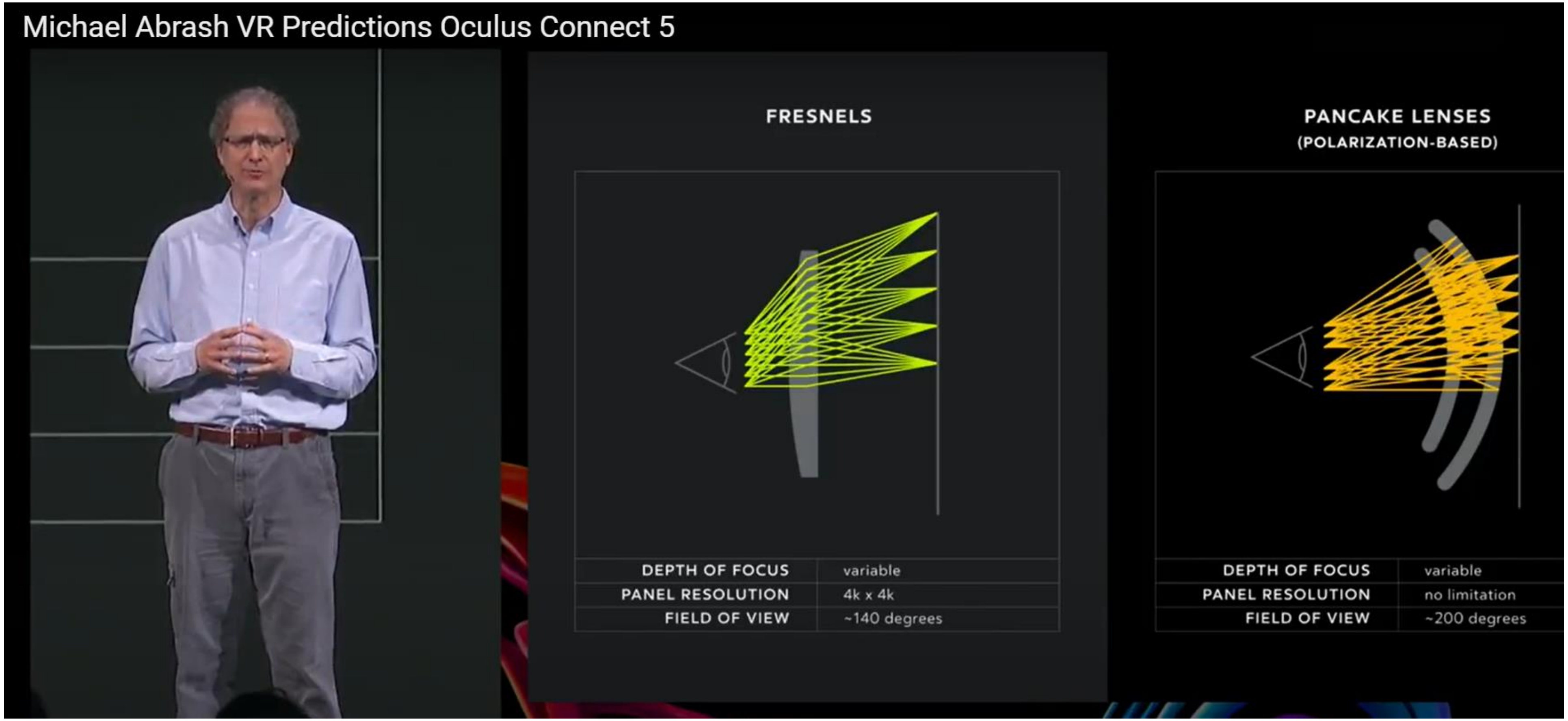
The Original Pancake lens collimator

designed for a CRT image generator



Main problem: not efficient – max theoretical 25% . Possible Solution: lasers or micro LEDs

Pancake lenses becoming more popular



https://www.youtube.com/watch?v=uUdZFge6ldI

AR companies' partnerships with μLED companies

WaveOptics Announcing a "Strategic Supplier Partnership" with Jade Bird Display.

WaveOptics is announcing a strategic partnership with **JBD** for their 0.13" VGA (640x480 pixel) green-only MicroLED microdisplay. To some degree, this simply makes it official (more on the precursors in a bit). WaveOptics has named the associated development kit "**Leopard**." The development kit version is going to suppoı 27-degrees FOV, monocular (right eye only available), and with (only) 4-bits (16-shades) of green. It is battery powered and free of cables.

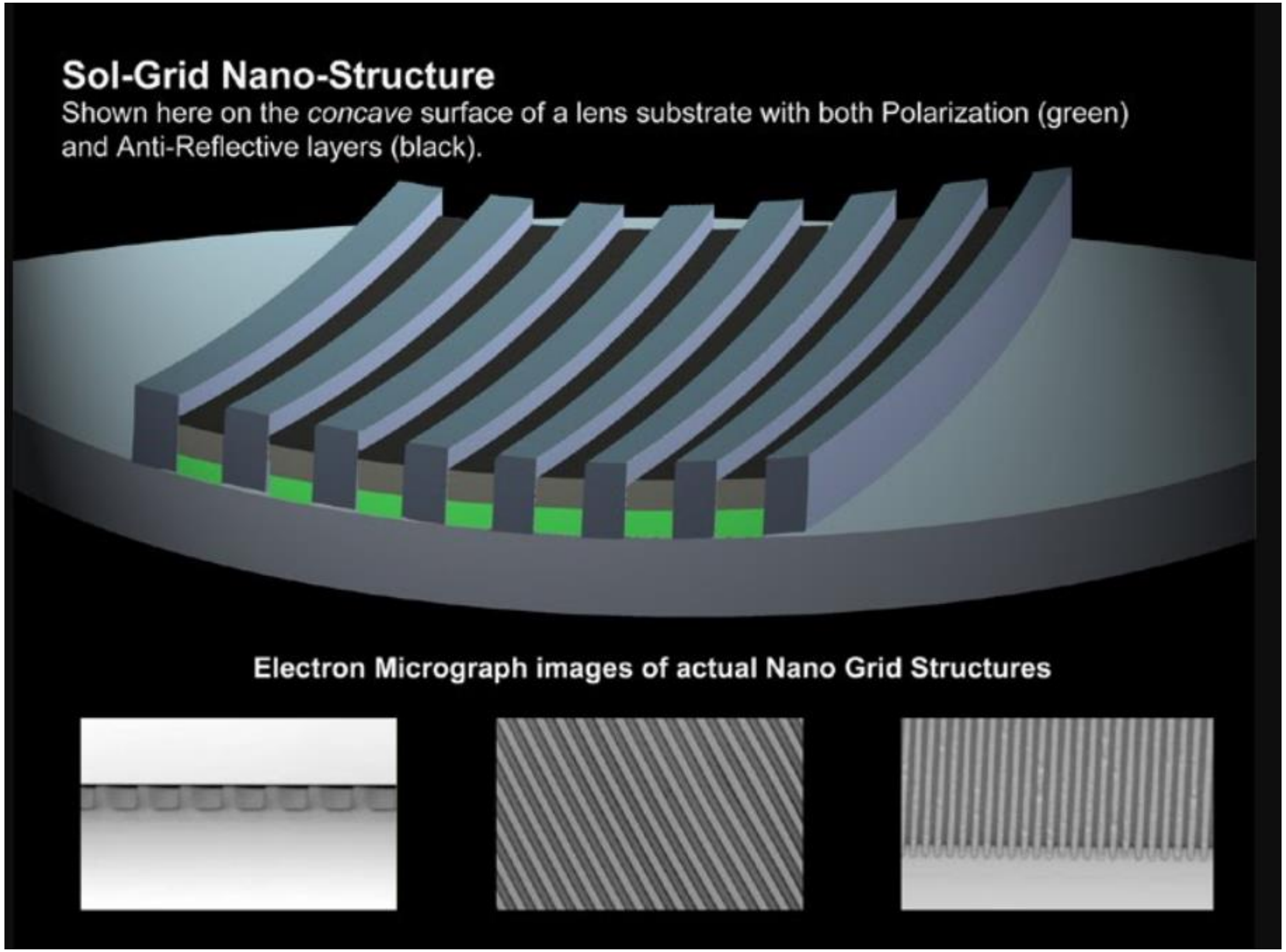
From Carl Guttag blog, Aug 2021

May 2019

Vuzix and Plessey Enter into a Long-Term MicroLED Supply Agreement

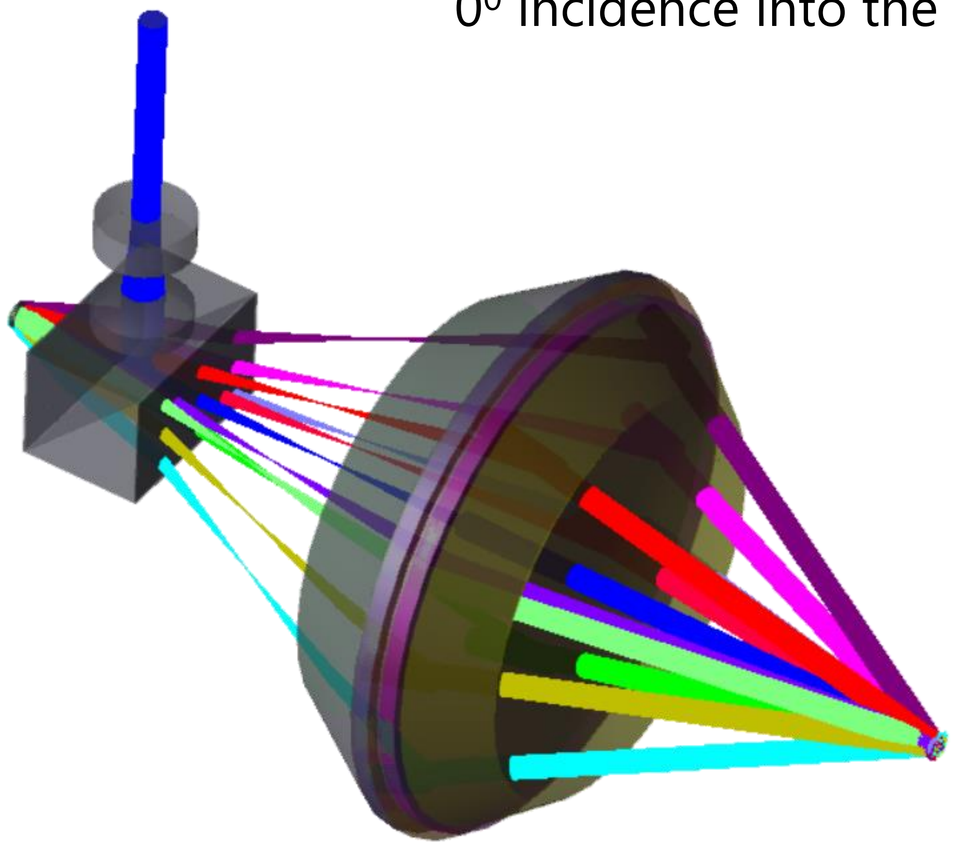
VUZIX

THE FUTURE OF POLARIZED EYEWEAR
SOL-GRID

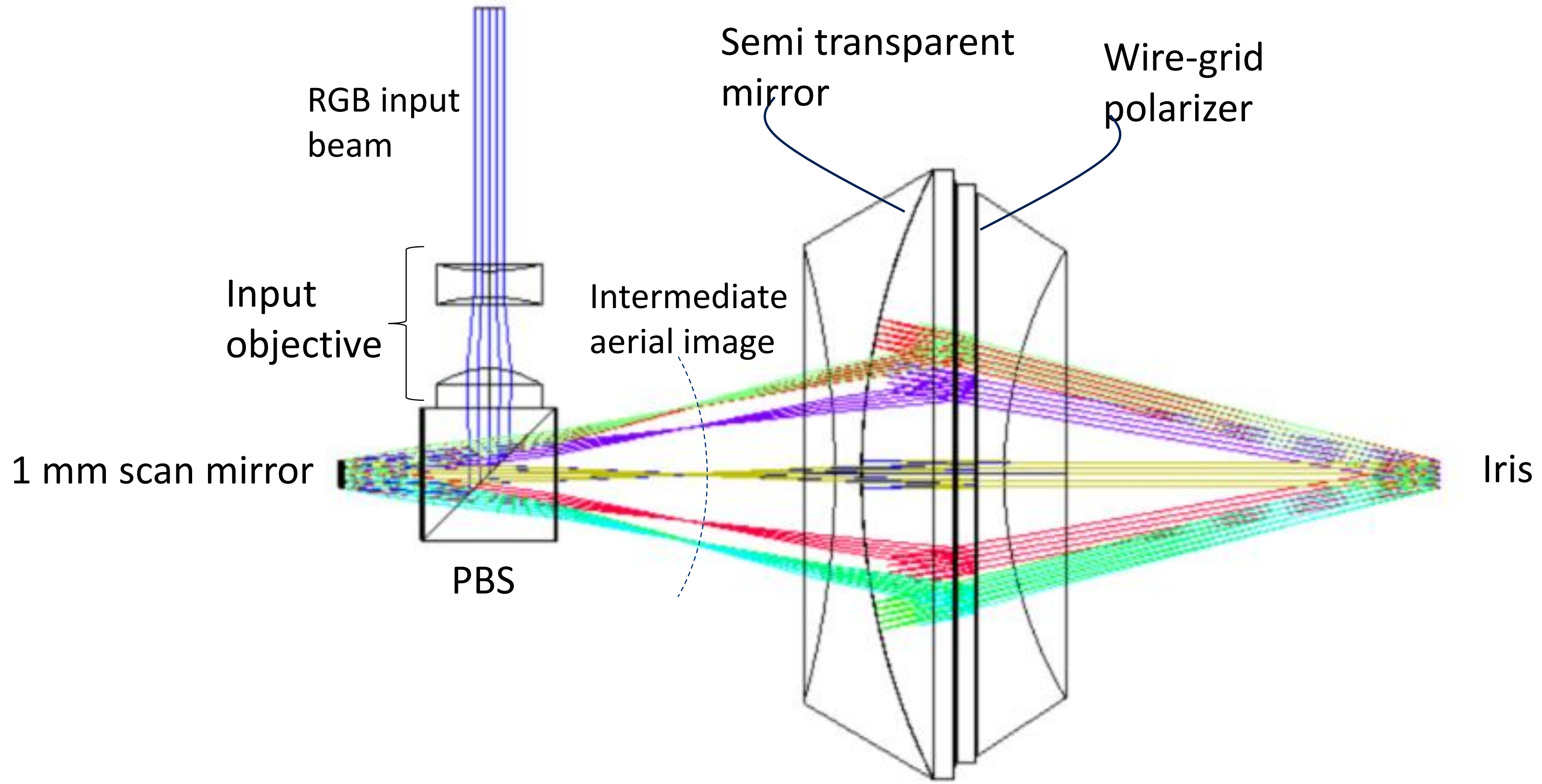


Pancake lens used as relay of the scan mirror to iris

Total FOV 43^0 by 25^0
0^0 incidence into the scan mirror

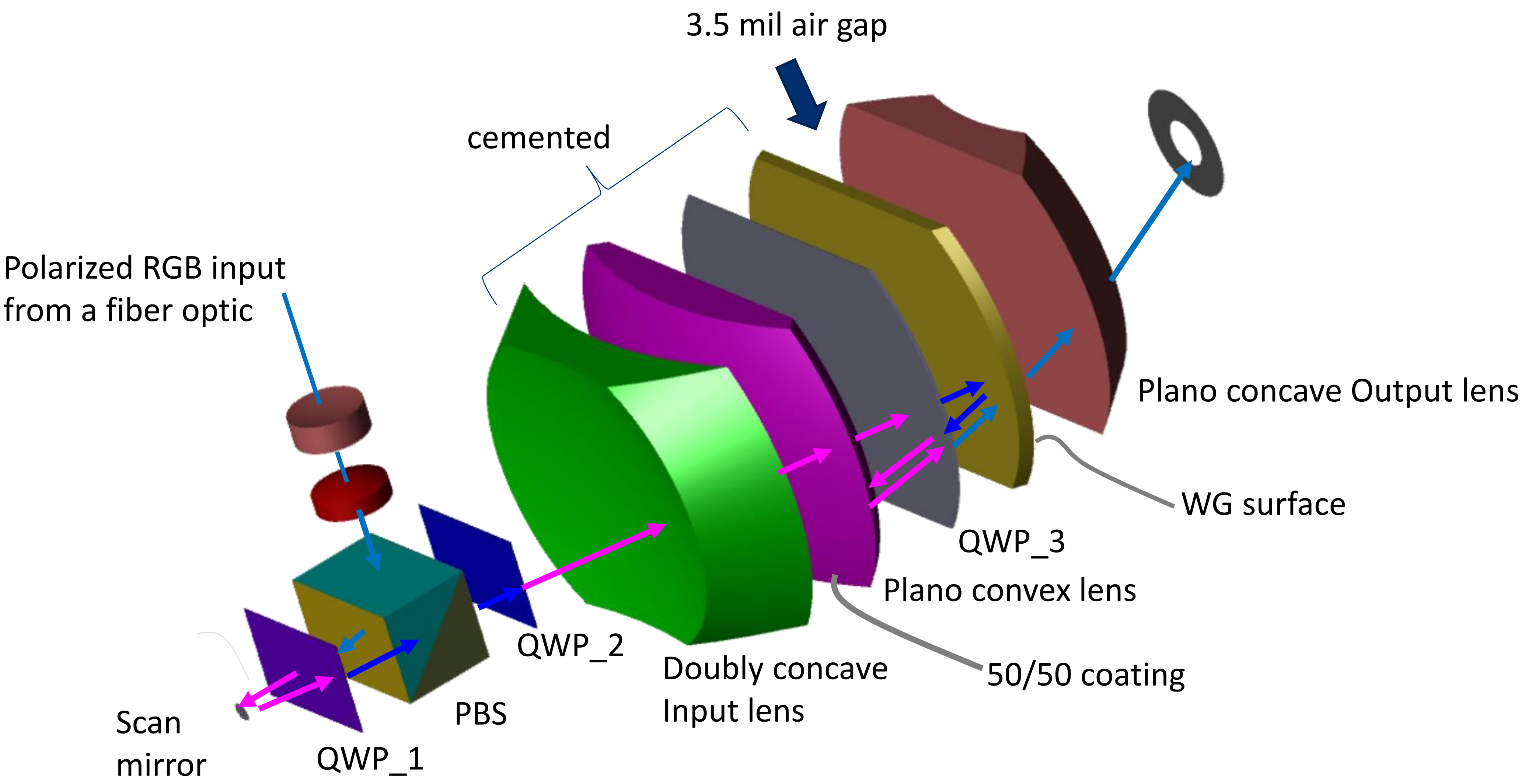


Layout from a collimated RGB beam to the iris



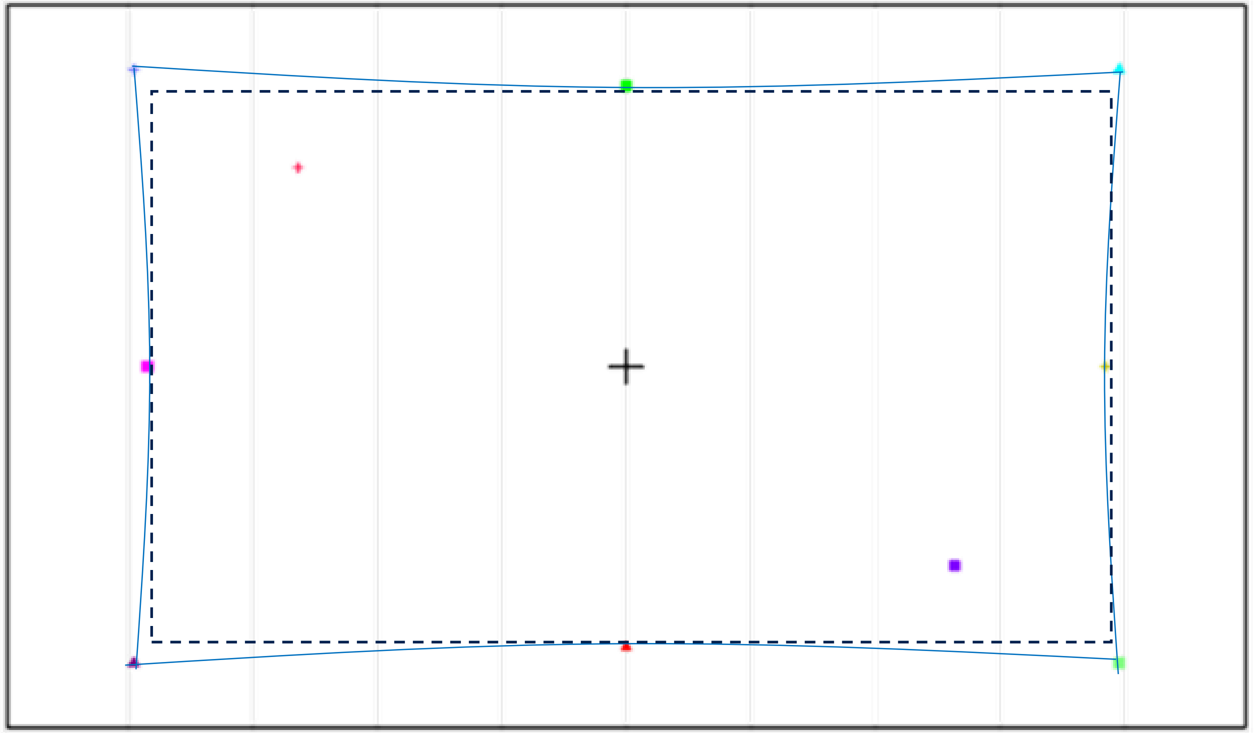
All curved surfaces centered on the scan mirror or the iris

Exploded view and polarization propagation



Using the input PBS reduce the keystone distortion and smile generated by the scan mirror

The 1:1 pancake lens itself introduces no distortion (or coma for all its orders)

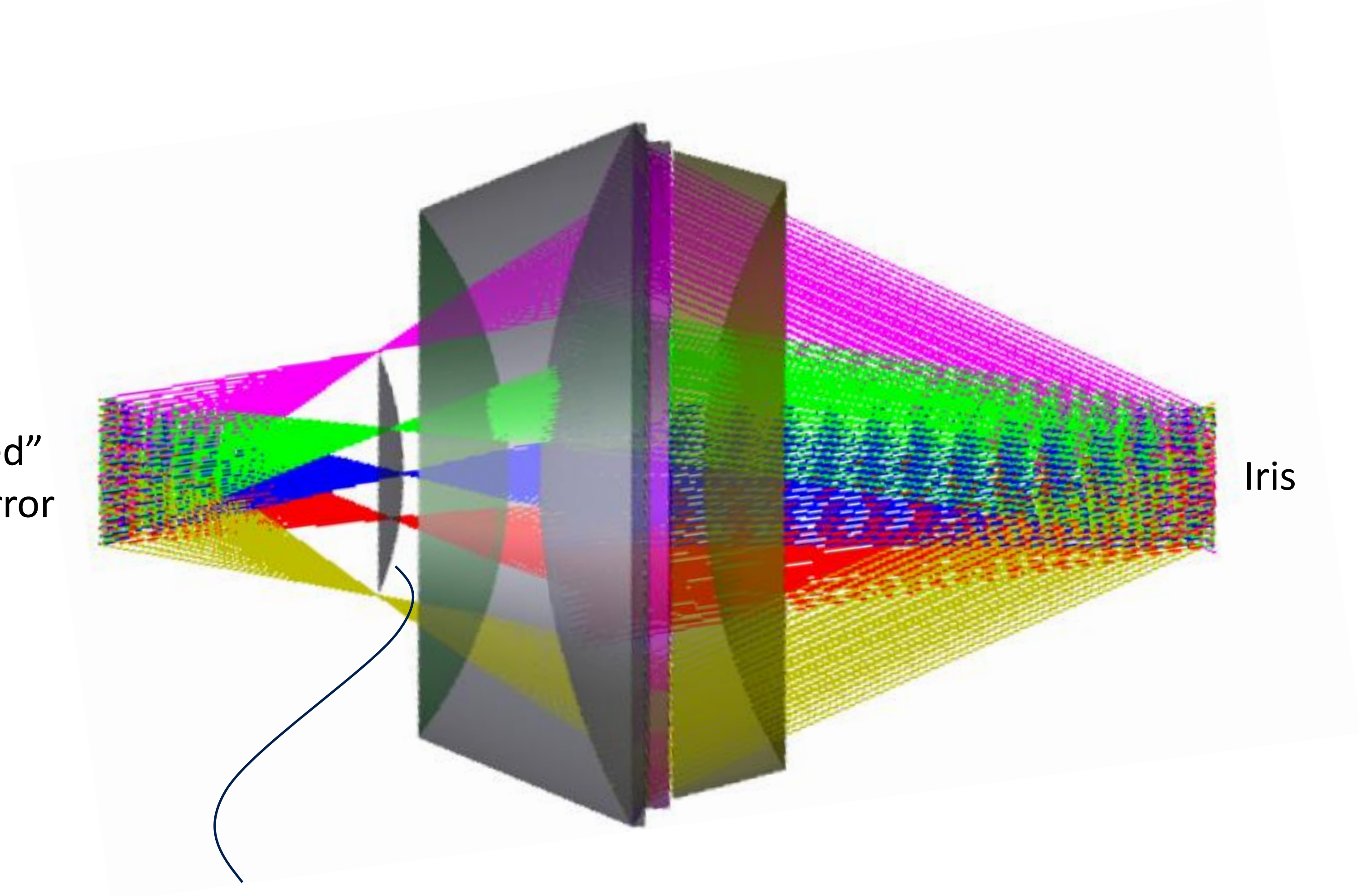


Note: the distortion could be further reduced with aspherics on the entrance and exit pancake surfaces

Enlarging the eyebox

•

“enlarged” scan mirror

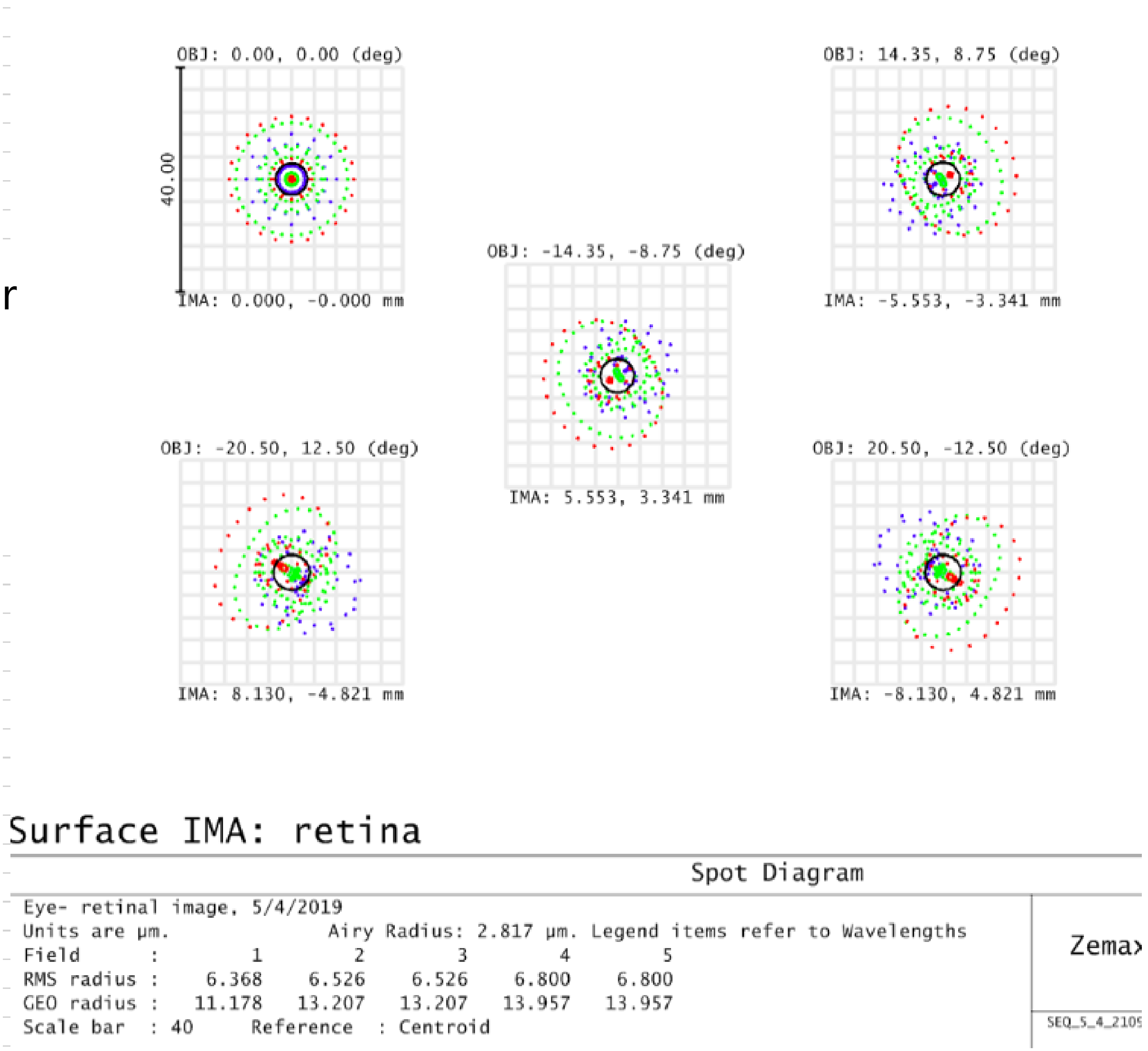


Iris

Placing a diffuser= NA expander at the curved input focal surface

Resolution with expanded pupil

Note: in this sequential analysis we use fields for the different scan angles. In the system analysis including the input beam shaper , the PBS and the scan mirrors –we use multi configurations for the different scan angles

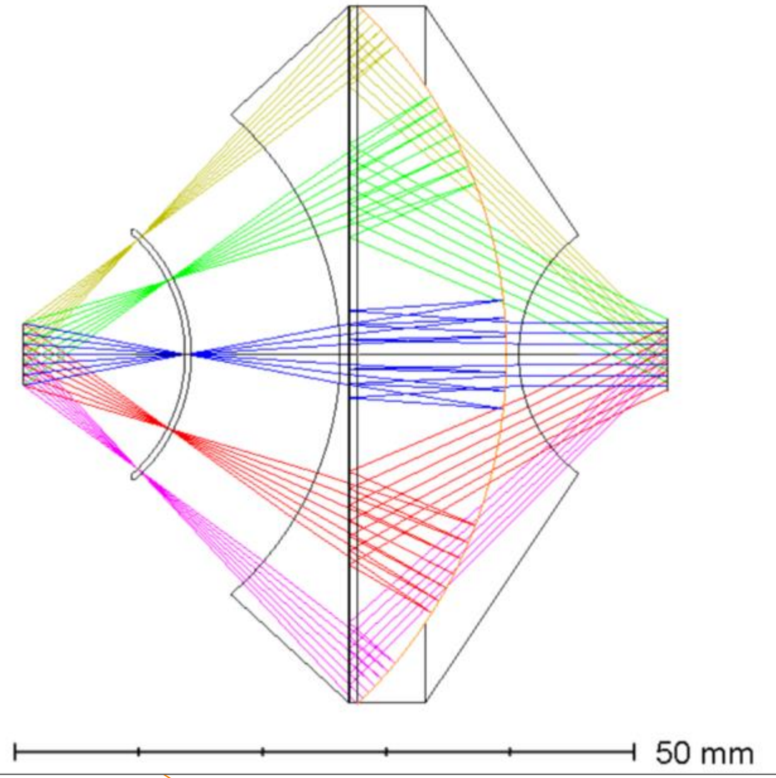


Spot sizes at the “retina” with a test lens with f=21mm

Thus 21μ=1mr and 6.2μ =1′

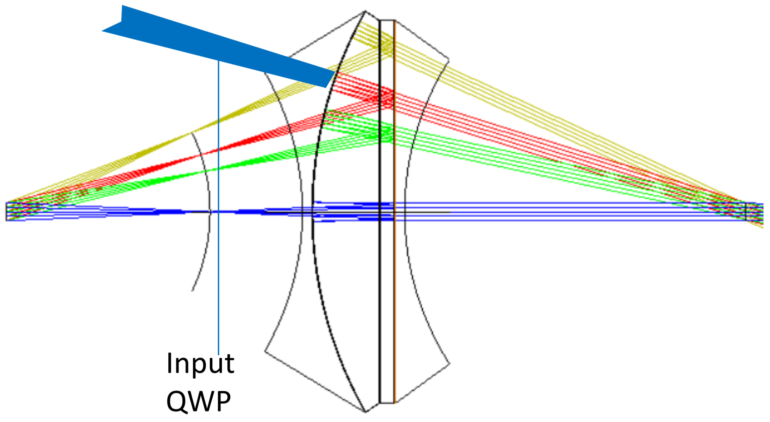
Enlarging the field of view to 84^0

-



Pancake lens isomers

All isomers need to have two QWPs.



1. Curved 50/50 surface followed by the flat reflective polarizer (the preferred embodiment)

2. flat reflective polarizer followed by a curved 50/50 surface - half of the light is directed to the eye and needs to be blocked with a circular polarizer

3. flat 50/50 surface followed by a curved reflective polarizer

Curved reflective polarizer patented by www.sol-grid.com

4. Curved reflective polarizer followed by a flat 50/50

On merit functions

We usually start with RMS spots
We really usually want good MTFs
RMS spot are related to the slope of the MTF curves at MTF origin

As we get closer, we switch commonly to wavefront to get better MTFS. This is because the Strehl Ratio is representing the volume under the OTF surface and the Strehl Ratio for a corrected system is related to the wavefront variance through the Marechal relation.

But: if the system final system SR is not going to be better than about .8 then the Marechal relation may not hold and using the wavefront may not result in improved MTFs so we may have to add say some MTF operands or just use the SR operand.

Converting Sequential to non sequential on Zemax

- Generally, the conversion is easy either by using the Zemax utility "convert to NSC group" or manually
- How to model wire grid polarizer in NS?
- How to a Jones element for large angles
- How to convert Q polynomials to NS

Modeling of a wire grid polarizer on Zemax

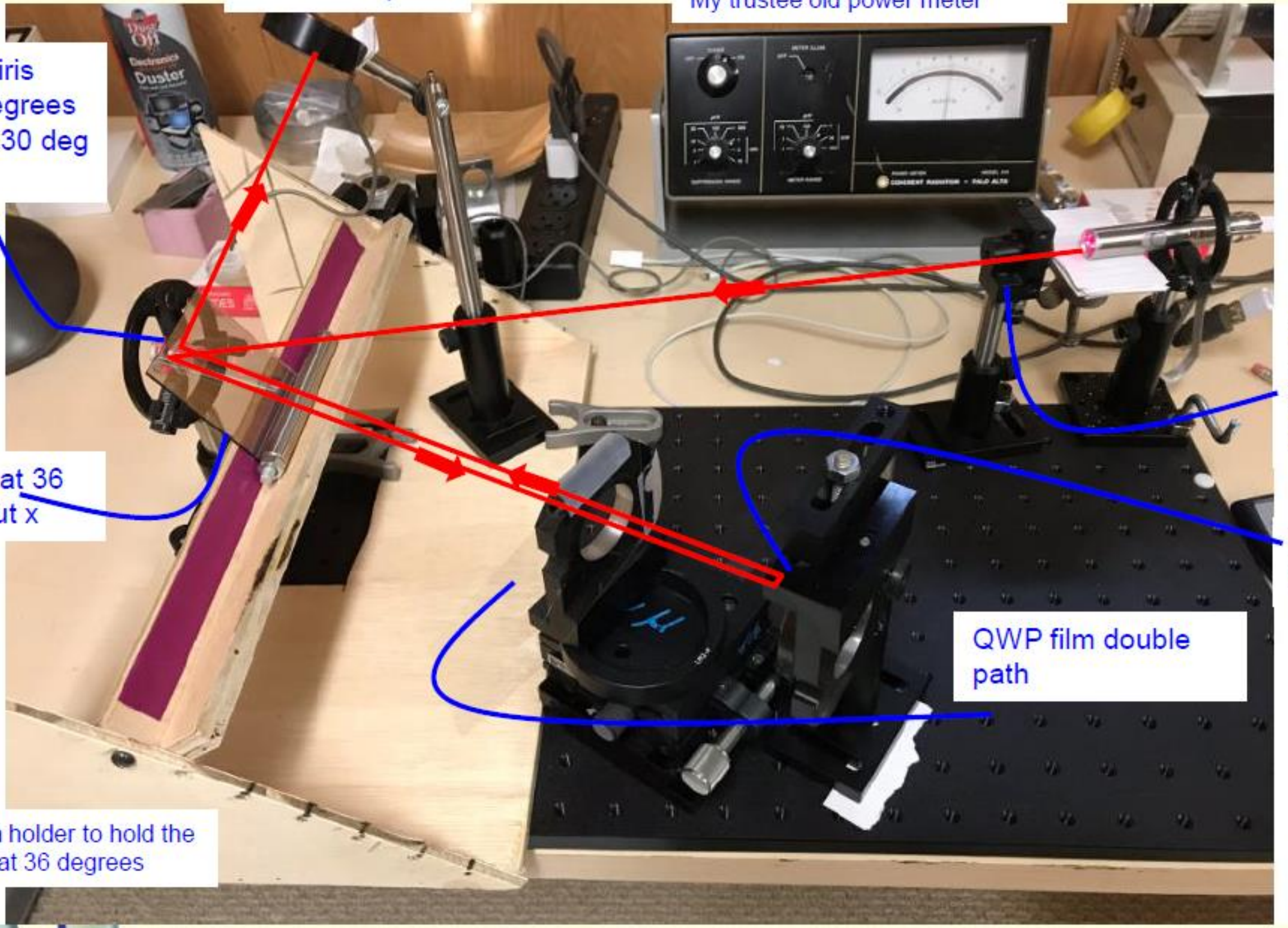
How to model the wire grid splitter on Zemax?

1.DBEF efficiency numbers are not accurate (as the Zemax manual says) at large skew angles.
2.The usual S and P definition do not work either since **S and P are local coordinates** for a specific incident angle and the wire grid works on the **global x and y coordinates**

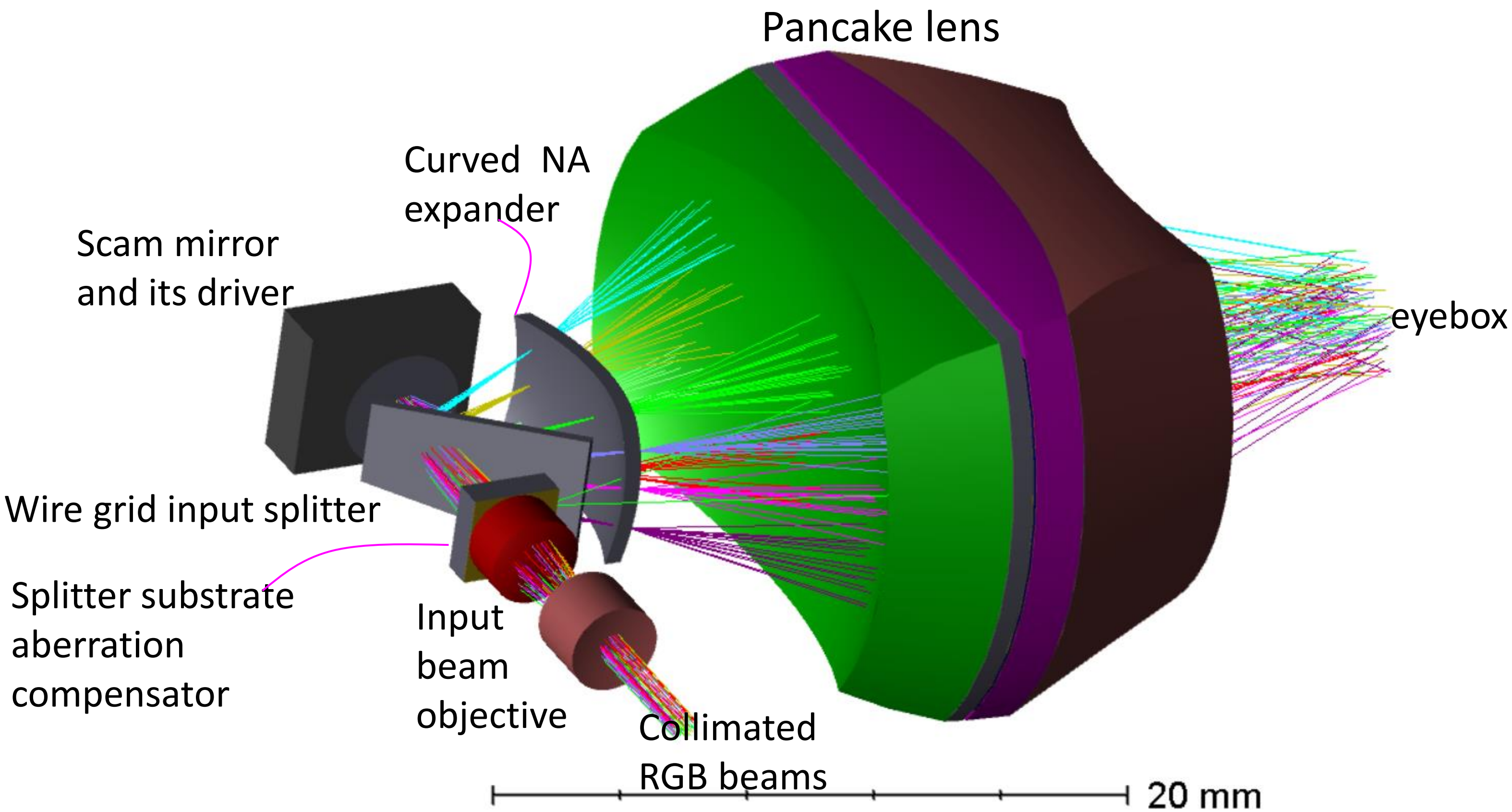
3.Lumerical and the **Zemax_interoperability_metalens_initial.lsf**
I don't design meta lenses or wire grids . I buy and use them and have their specification say from Moxtek. I want to plug the specifications as I do with coating tables when I get a coating specs.   When I design Wire Grid polarizers I happen to use GSOLVER not Lumerical

4. My non-optimum solution: verify the NS design with a lab set up

Breadboard


Power meter probe
My trustee old power meter
Mirror at the iris rotated 15 degrees to obtain the 30 deg FOV in x
laser
Glan-Thompson polarizer allowing polarization in the y direction
Moxtek PBS at 36 degrees about x
Mirror simulating the combiner
QWP film double path
Wooden holder to hold the moxtek at 36 degrees
Duster

Non sequential model

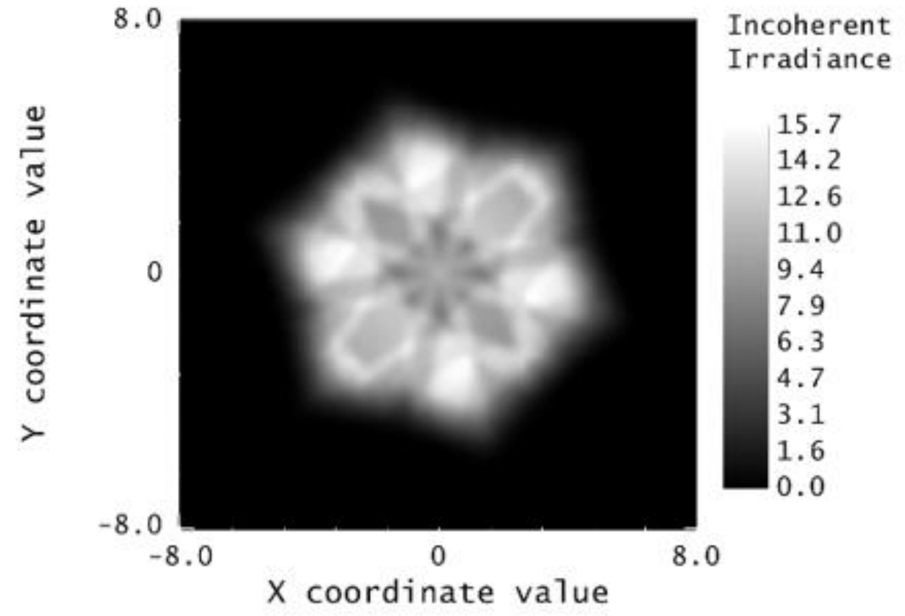


The NA expander modeling

This is still work in progress where we explore 3 main possibilities
1 Curved diffusers
2 one sided curved multi lens arrays in hexagonal packing
3 Two sided curved multi lens arrays in hexagonal packing as per the Hakan reference bellow

The issue at had is to provide the divergence needed but avoid the visibility of the expander microstructures (without resorting to dithering the expander) and provide for relatively uniform eyebox exposure.

Iris exposure as the beam scans a few lenslets within one pixel at the NA expander made of one sided MLA



Reference: **Microlens-array-based exit-pupil expander for full-color displays**

Hakan Urey and Karlton D. Powell

Q aspherics on non sequential model

* The latest update has added Q-Surface not a lens though
* Use the aspheric tool in sequential to convert from the sequential Q to the standard
* Use these coefficients with the even aspheric lens object.
* If more then 16 coefficients are needed - use the Odd Extended Aspheric Lens and kill the odd terms.

OR: lately I learned that I can use the new NS Q **surfaces** with the **Compound lens object** which lets you place the Q-Surfaces on its input and output surfaces.

Interfacing with the mechanical designers

- I am not currently using the LensMechanix on Zemax- I am a bit more old fashioned and usually create the STP or IGES files and send to the mechanical designers and then import their designs in my non sequential and look for say ghosts

Thank you for listening.

Questions?

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Q&A Session will now begin.