Optical architectures for see-through wearable displays

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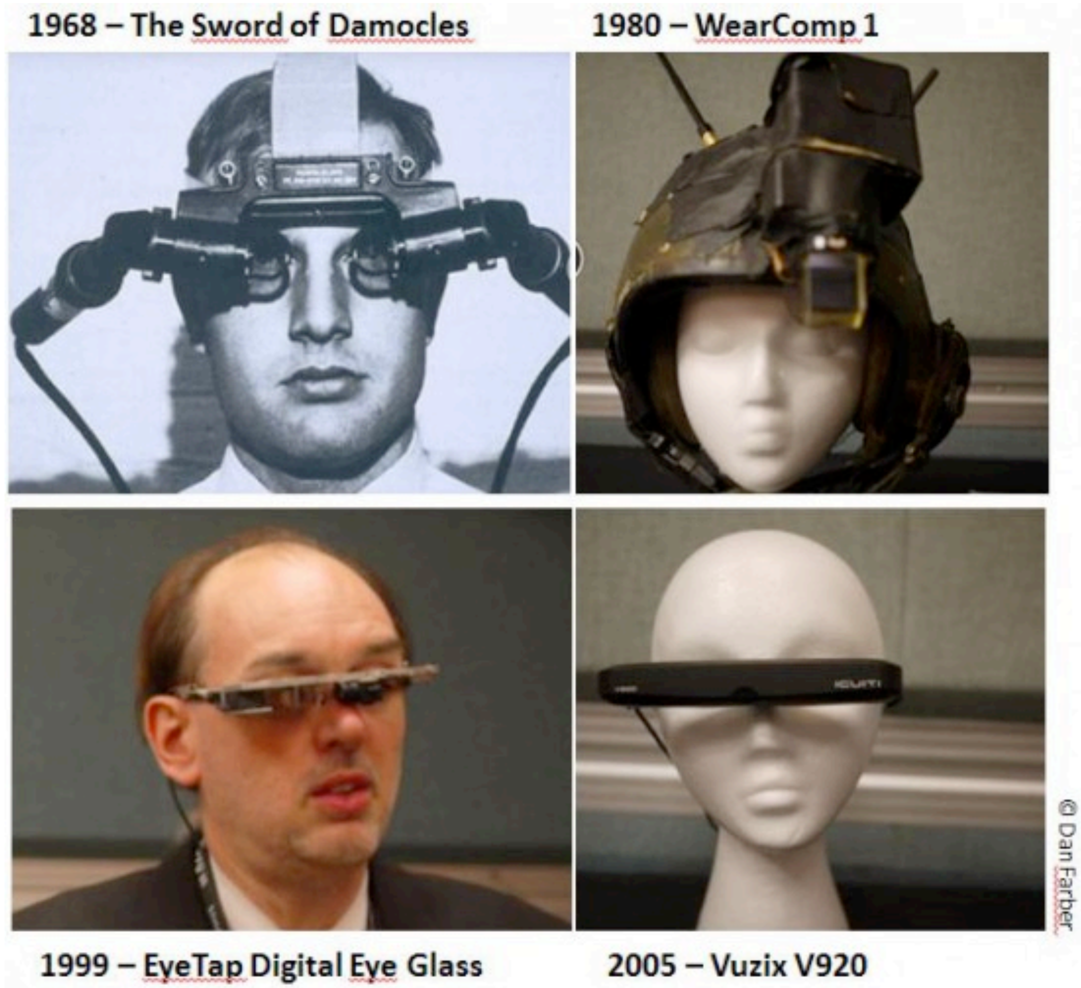
Outline

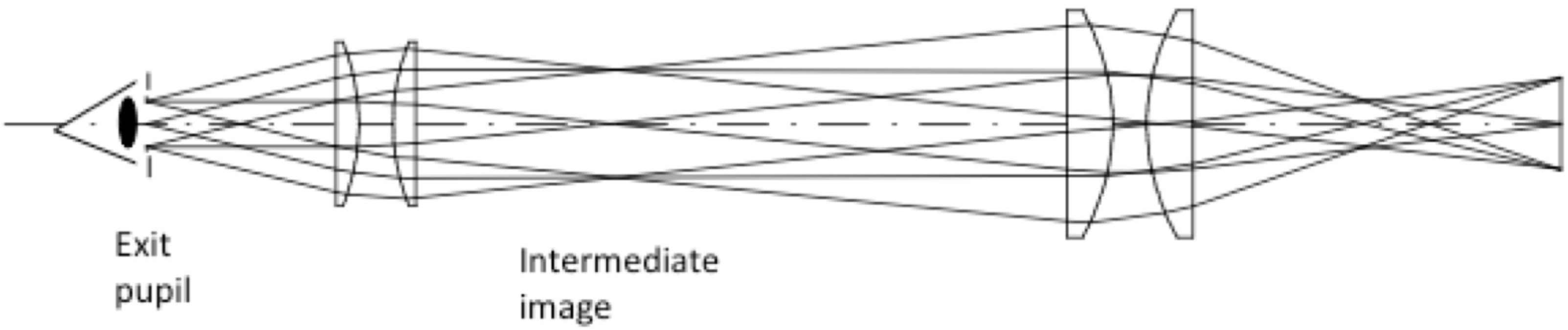
1) The coming of age for wearable displays: a bit of history
2) Today's HMD/smart glasses market fragmentation
3) Optical architectures for see-through wearable displays
4) Microdisplays options for wearable displays
5) Wearable optical sensors

HMDs? Not new!

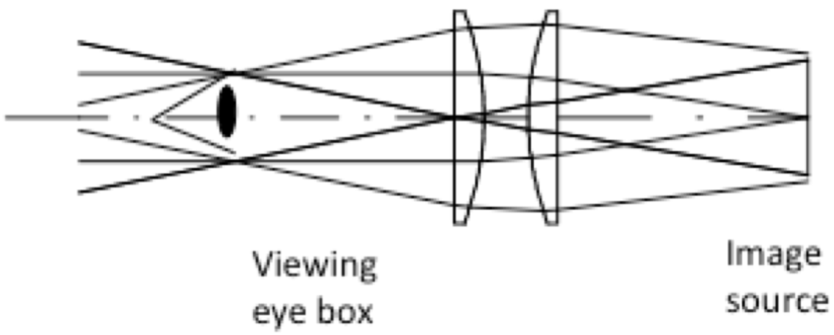

1968 – The Sword of Damocles
1980 – WearComp 1
1999 – EyeTap Digital Eye Glass
2005 – Vuzix V920
© Dan Farber

There are two main optical architectures for wearable display optics:

1) Pupil forming architecture



2) Non pupil forming architecture (magnifier)



Most of these architectures have been developped since the 70s

(newer BAE waveguide holographic combiner shown here on jet fighter pilot helmet)

A decade ago, the HMD market was split between low cost gadget occlusion HMDs (low resolution video players, no sensors, no connectivity)

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Today, thanks to the development of smart phones and associated chips, sensors and apps, new markets are emerging, targeted towards different market segments.

Yesterday's HDM markets

Yesterday's HDM markets

The "great" ZOO"

Google

Yesterday's HDM markets

The "great ZOO"

Today's segmented market landscape

Connected glasses (no display)

Occlusion display smart glasses

See through smart glasses

Gaming HMDs

Professional HMDs

Defense HMDs

Requirements for the various HMD market segments

Spec	Smart glasses	Gaming headsets	Industrial HMDs	Defense HMDs
Industrial design	++++	+	-	-
Power consumption	++++	-	+++	-
Costs	+++	++	+	-
Weight/Size	+++ (forgettable)	+	++	+ (Helmet mounted)
Eye box	++++ (minor mech. adjustments)	- (dial in)	+++ (minor mech. adjustments)	- (dial in)
Rx glasses integration	+++ (combo /monolithic)	- (dial in)	+++	- (NA)
Full color operation	+ (mono to full color)	++++ (full color)	++ (multi color)	- (mono / multi color)
FOV	- (<=15 deg)	++++ (>90 deg)	++ (>30 deg)	++++ (>100 deg)
Contrast	+ (>= 100:1)	++ (occlusion)	++++ (>500:1)	++++ (>500:1)
Environmental stability	++	-	++++	+++
See through quality	++	- (occlusion display)	+++	+++
Mono/Binocular	Monocular	Binocular 3D	Monocular	Binocular 2D

Connected glasses (no or minimal display)

Ion Smart Glasses
Single LED alert light

Mita Mamma eyewear

Geco eyewear

Fun-Iki eyewear

Weight : 38.5g

Wireless : Bluetooth 4.0 wireless technology

Battery : Built-in rechargeable lithium-ion battery Charging via USB to power adapter

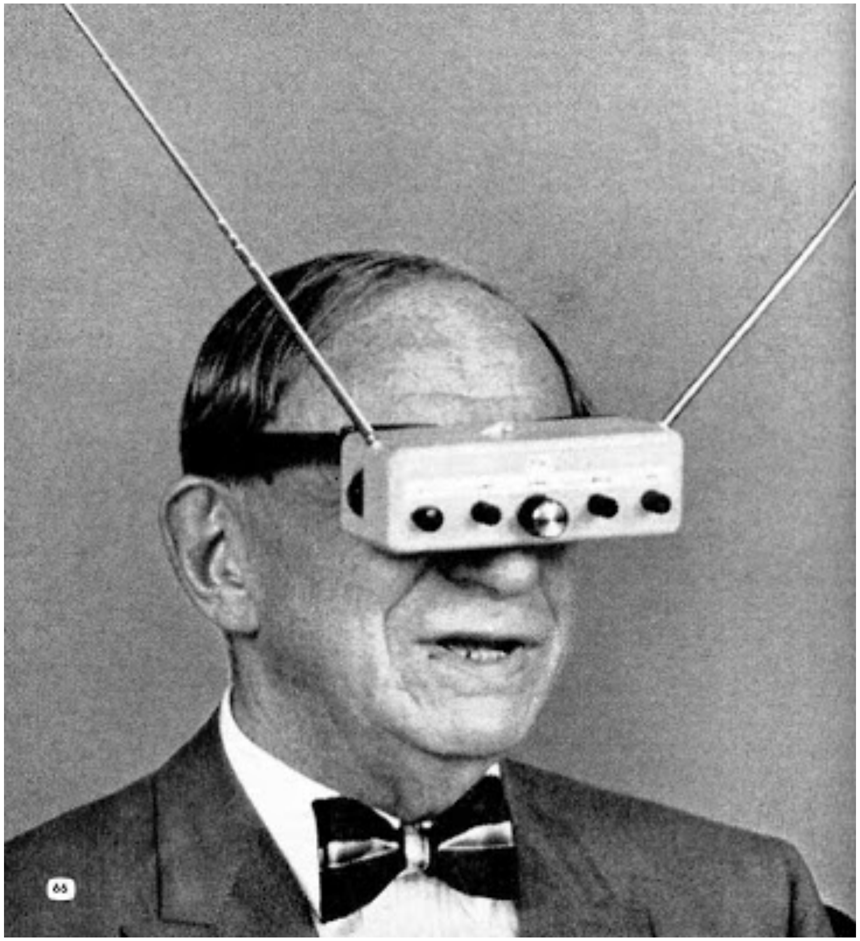
Light : Six Full colour LED light

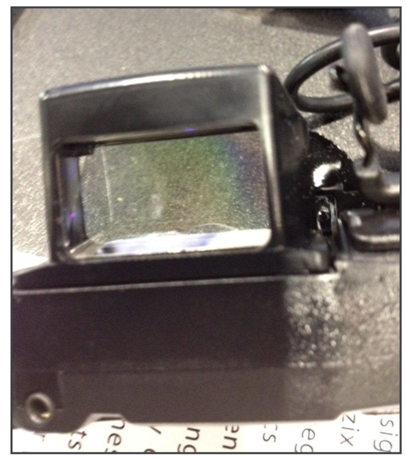
Audio : Built in speaker

Sensors : Accelerometer / Ambient light sensor

Button : One mechanical push button

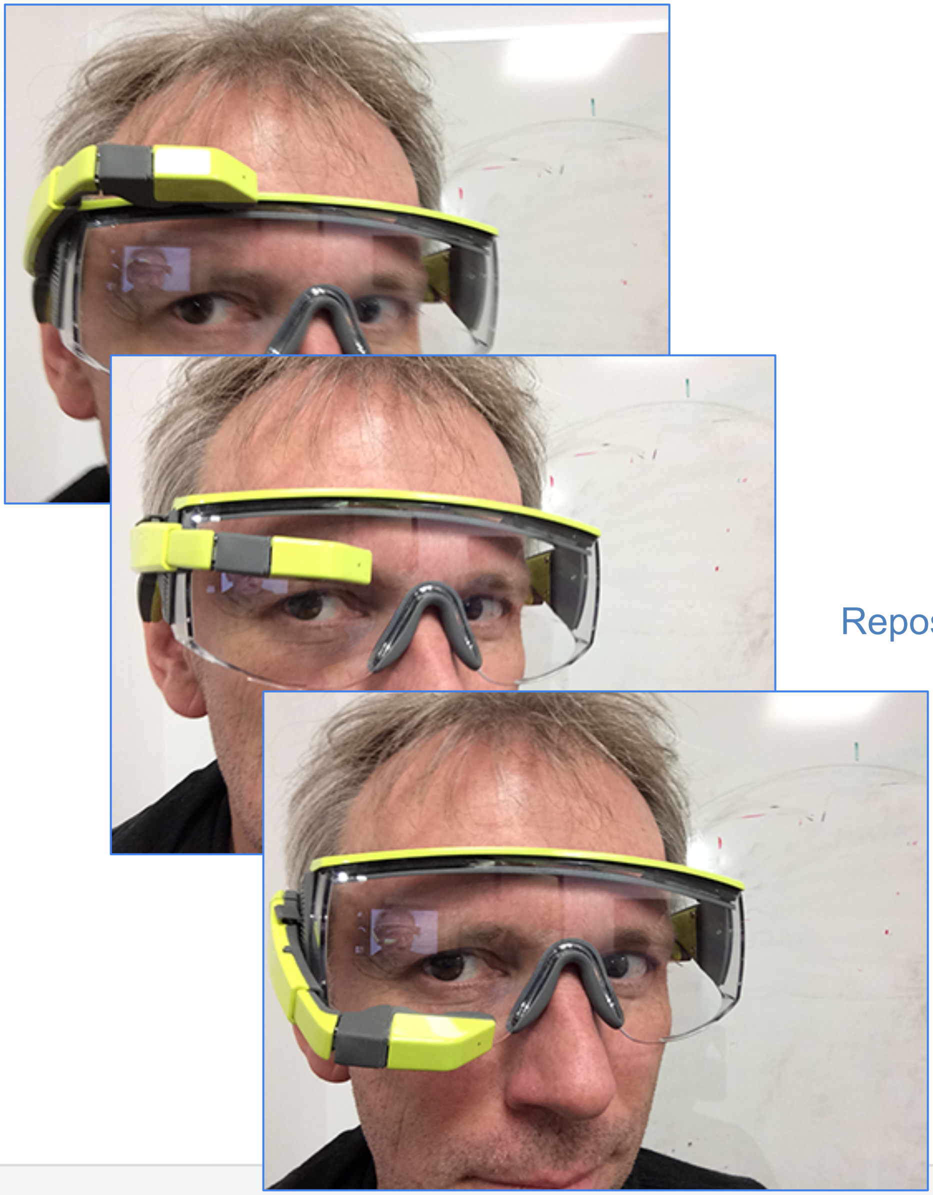
Occlusion smart glasses





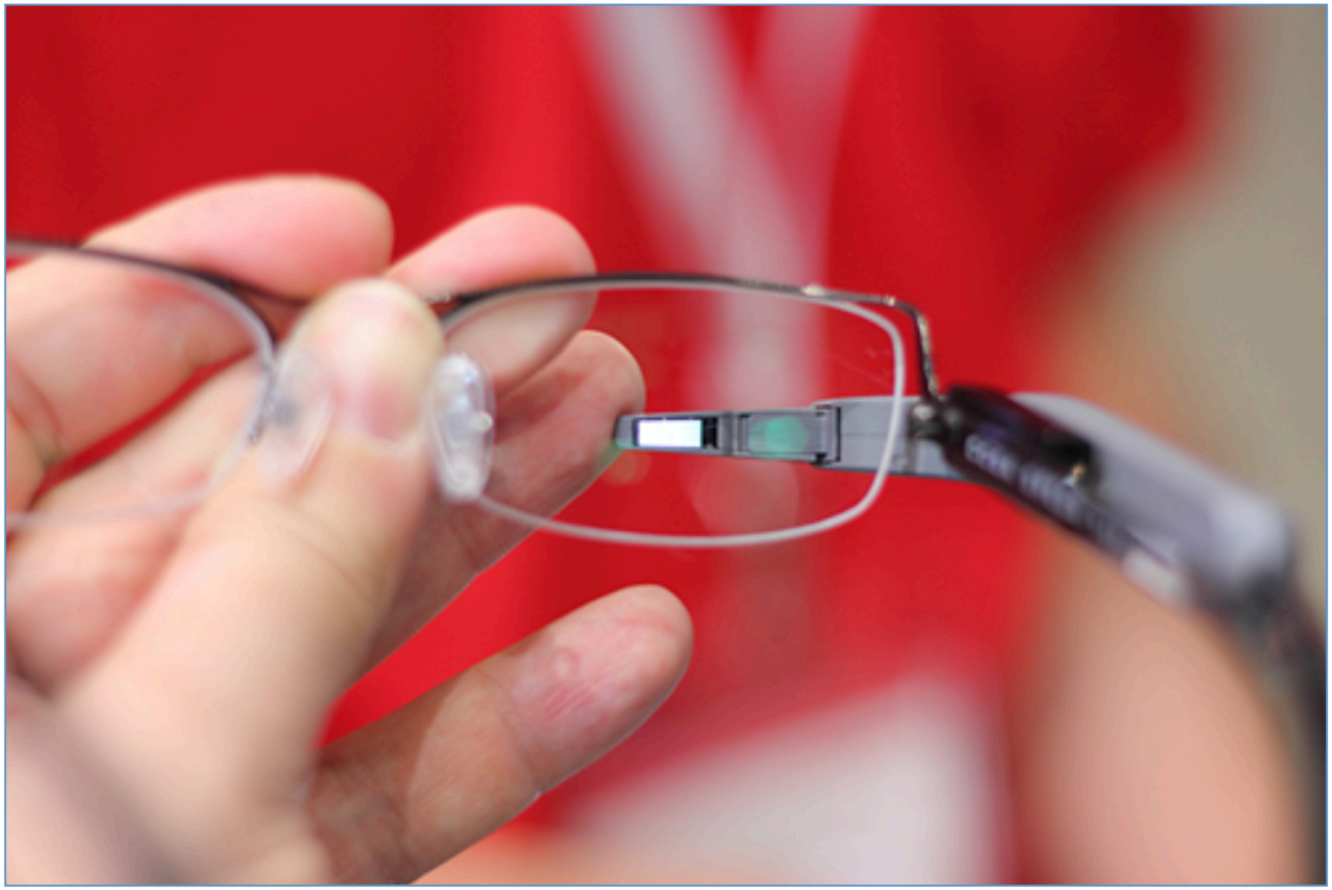
Vuzix Corp. Star 1200
Synthetic see-through via front facing camera

Vuzix Corp. M100
Conventional optical combiner, similar to MyVu Crystal, (non see through)
Good eye box since lens in front of eye



Kopin Corp.

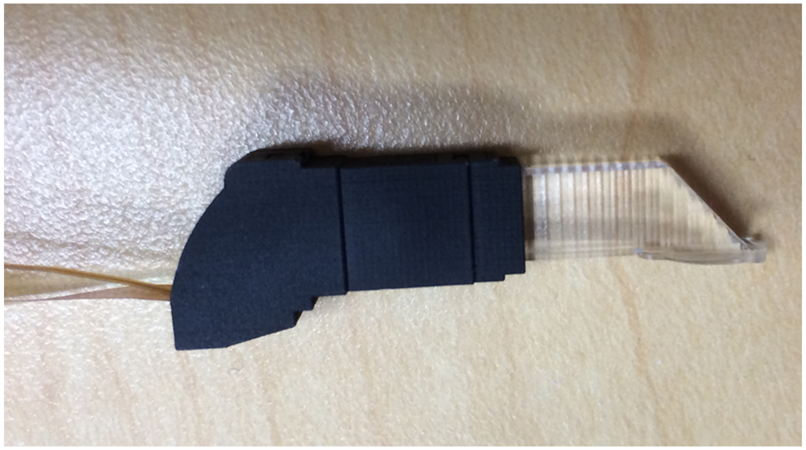
Repositionable occlusion combiners



Olympus Ltd. Japan
Tapered opaque light guide with 45 degrees mirror
(makes it “see through” since taper is smaller than eye pupil diameter <4mm)
Small eye box but can be relocated up or down since arm is flexible
(can also be stowed away)

Kopin Corp.

Example of integration of a tapered lightguide in prescription glasses



Telepathy One
Connected glasses, with tapered lightguide

Recon Instruments Corp.

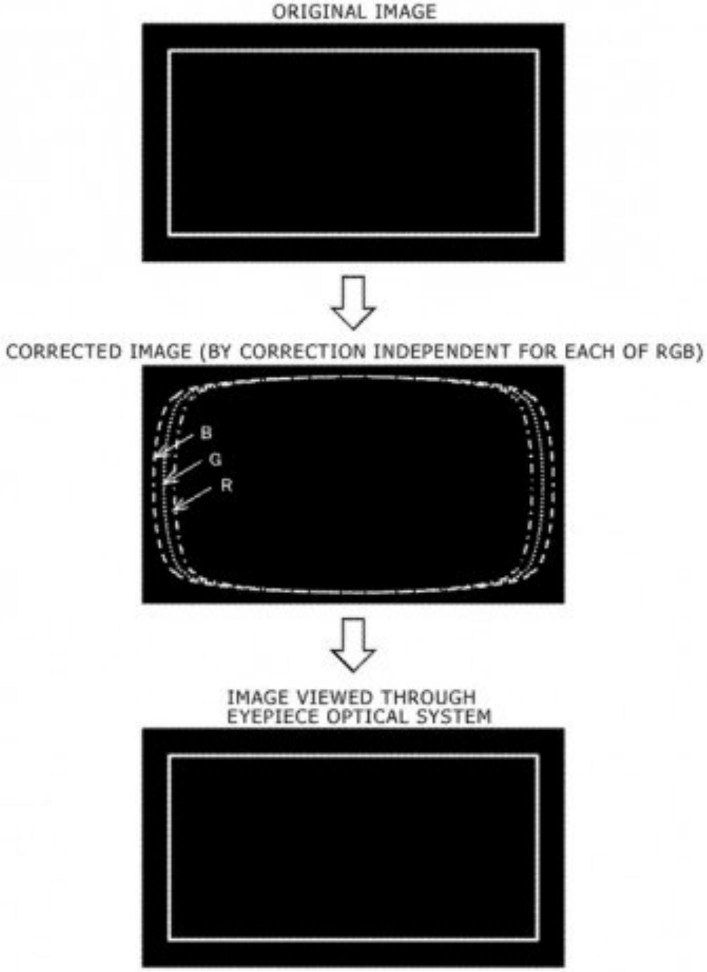
Integration of occlusion display in sky goggles and sport shades

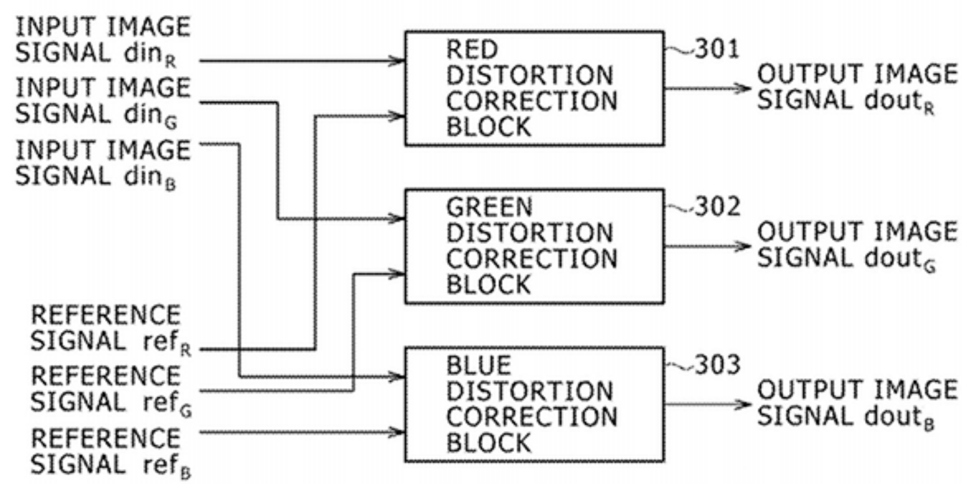
Gaming headsets

Oculus rift

Although Occulus rift optics are very simple, considerable efforts has been produced in various software algorithms for optical aberrations compensations such as distortion, color spread, etc…

FIG.25





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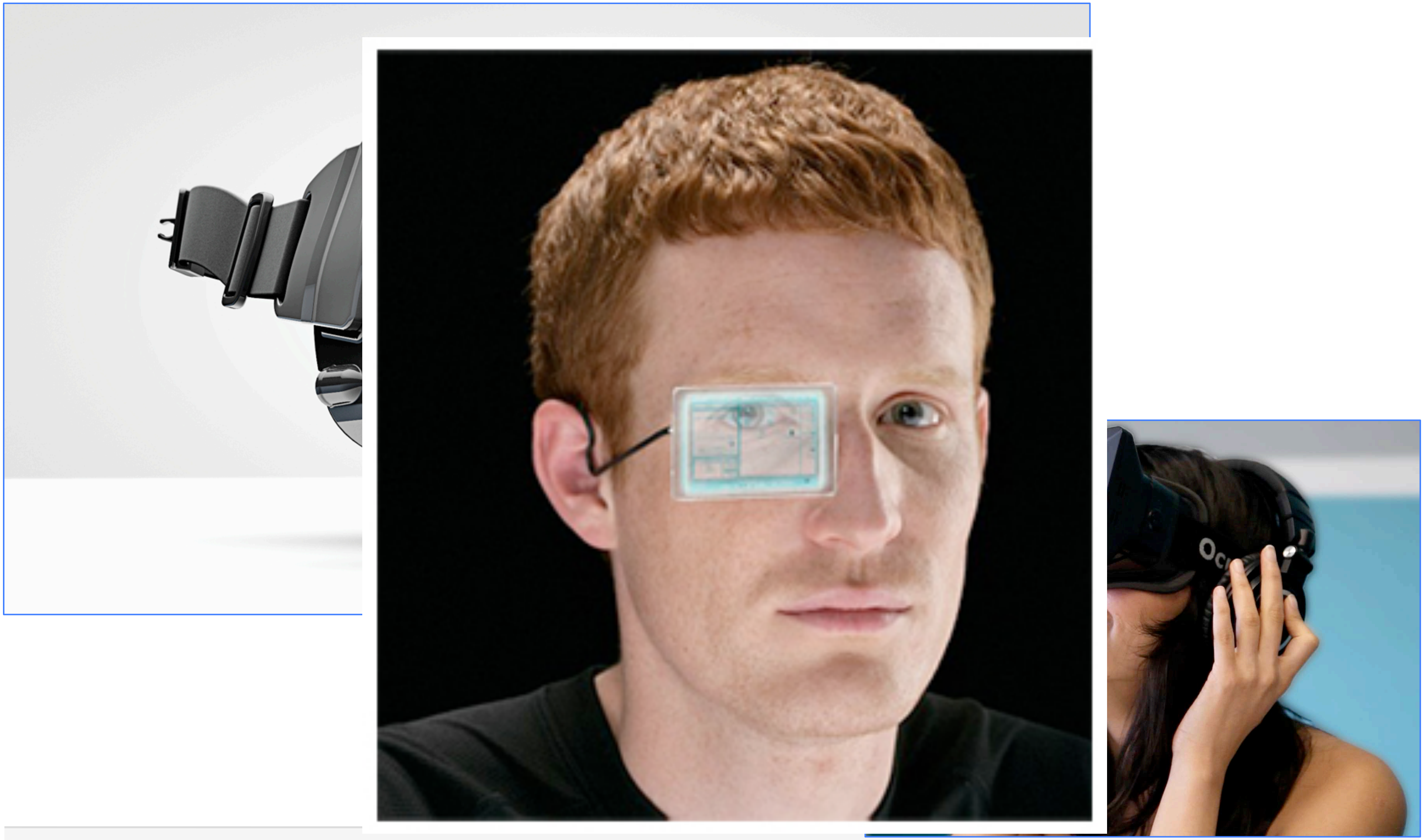
What's next?



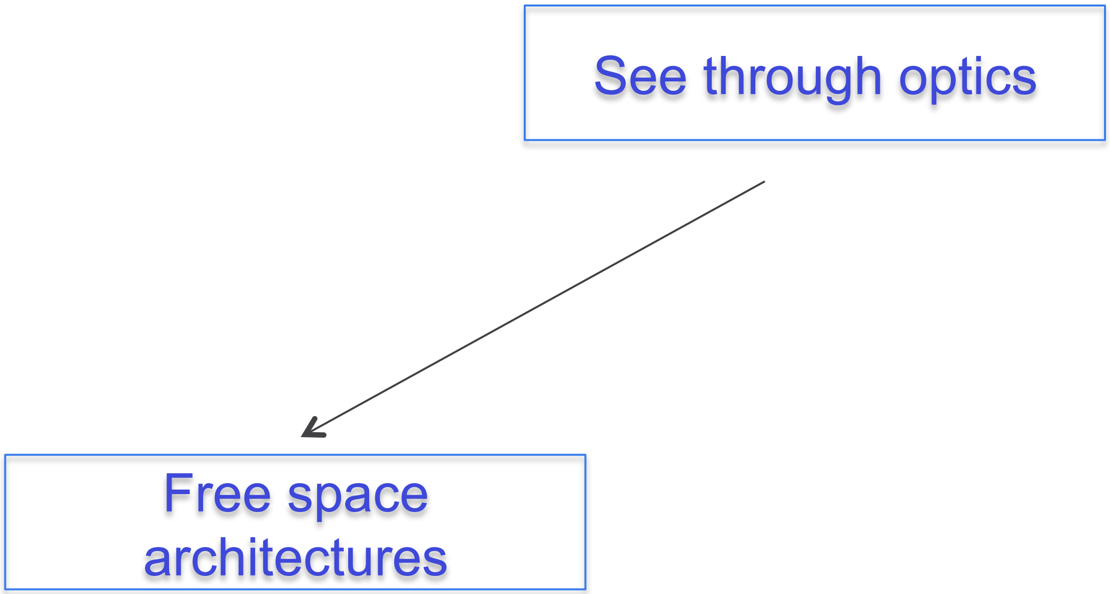
Interesting concept from Glyph

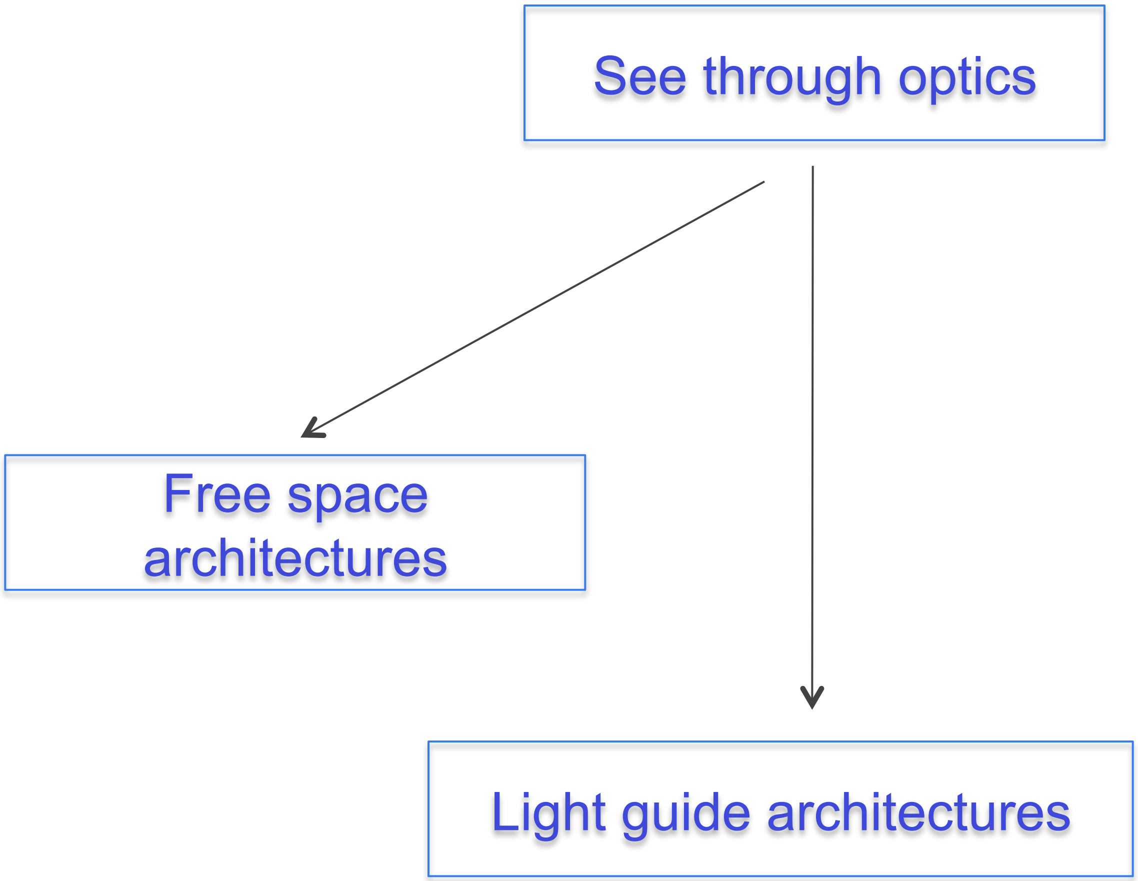
Sony's HMZ T2 3D glasses

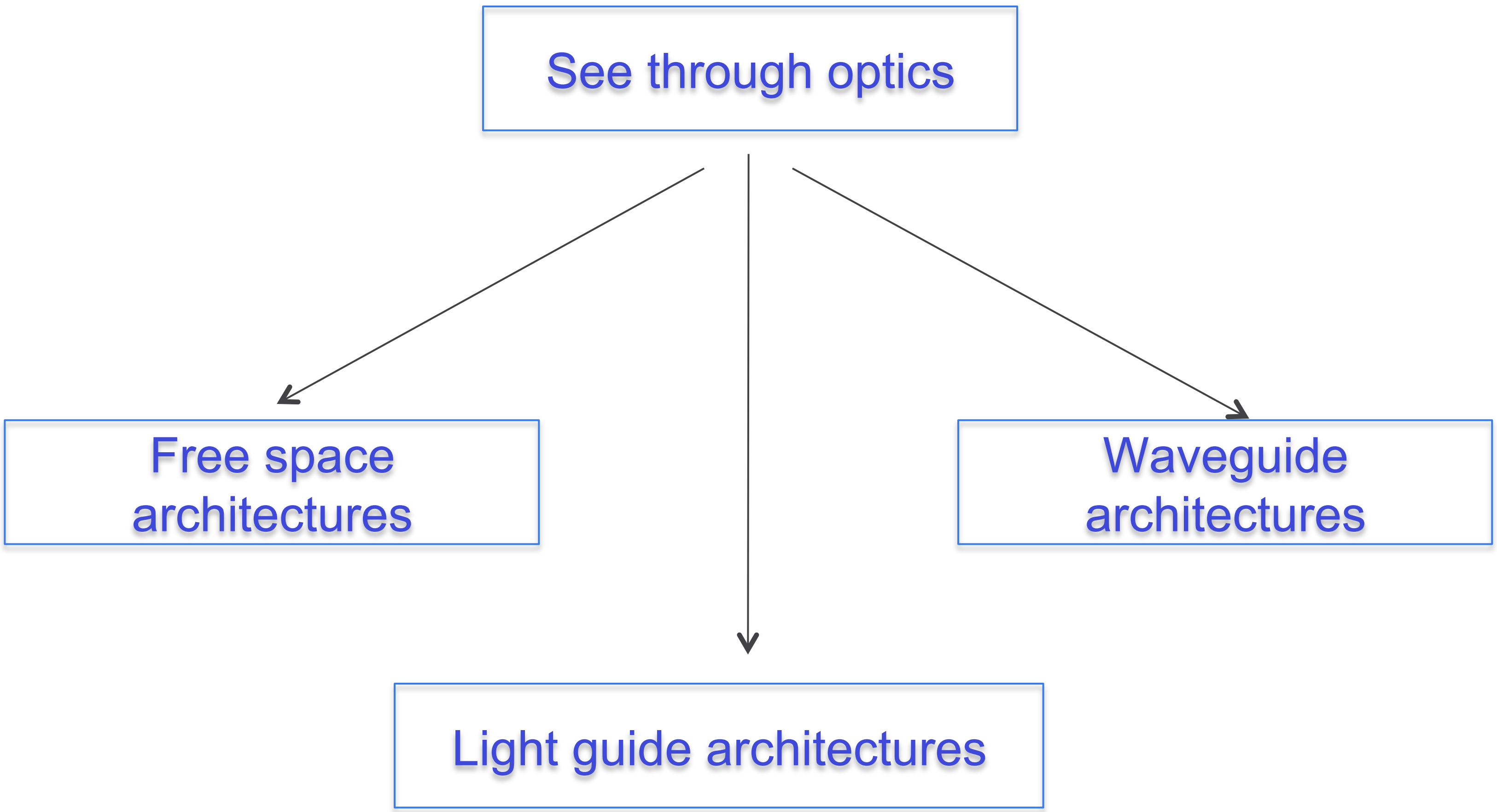
See-through smart glasses

See through optical combiner architectures

See through optics

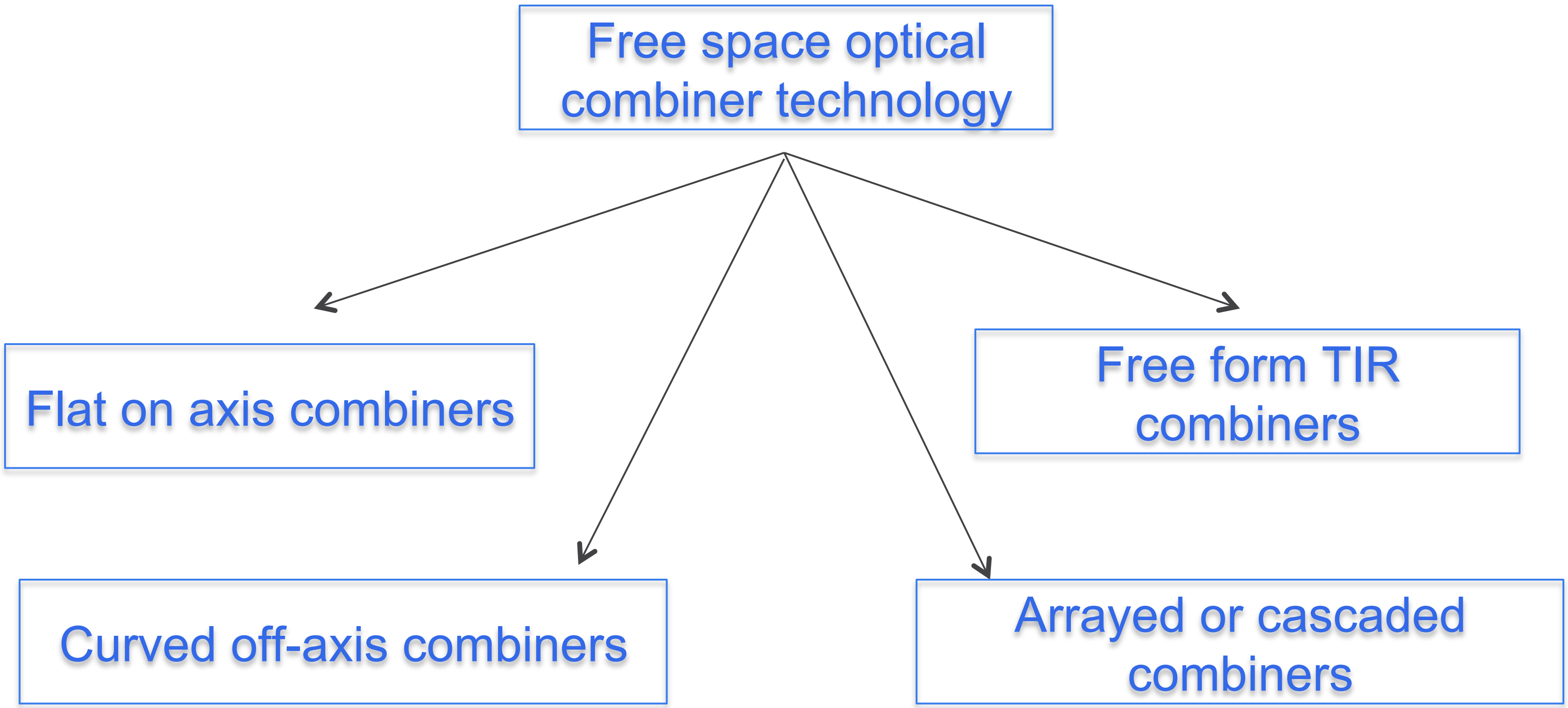

See through optics
Free space architectures

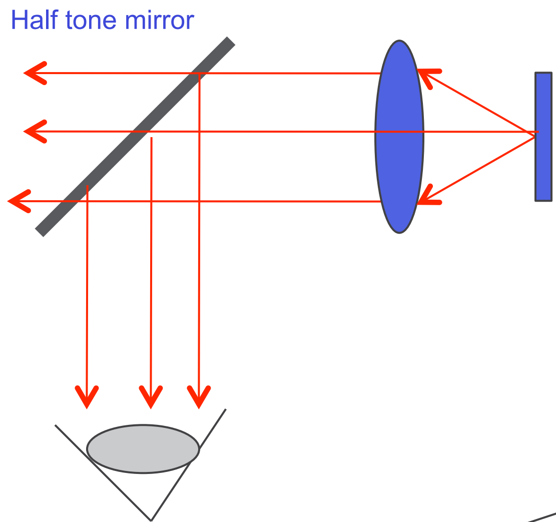

See through optics
Free space architectures
Light guide architectures

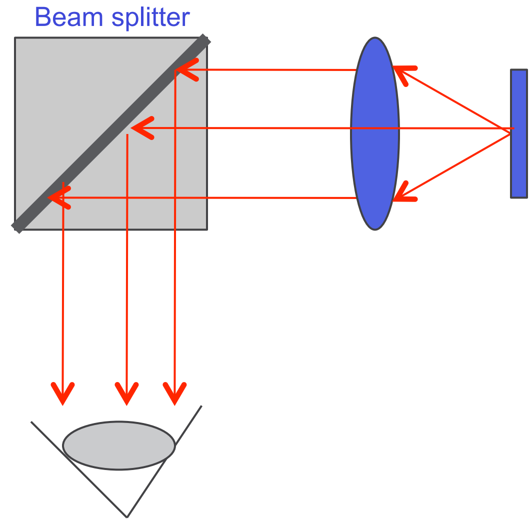

See through optics
Free space architectures
Waveguide architectures
Light guide architectures

Classification of optical combiners

1- Free space and guided space architectures







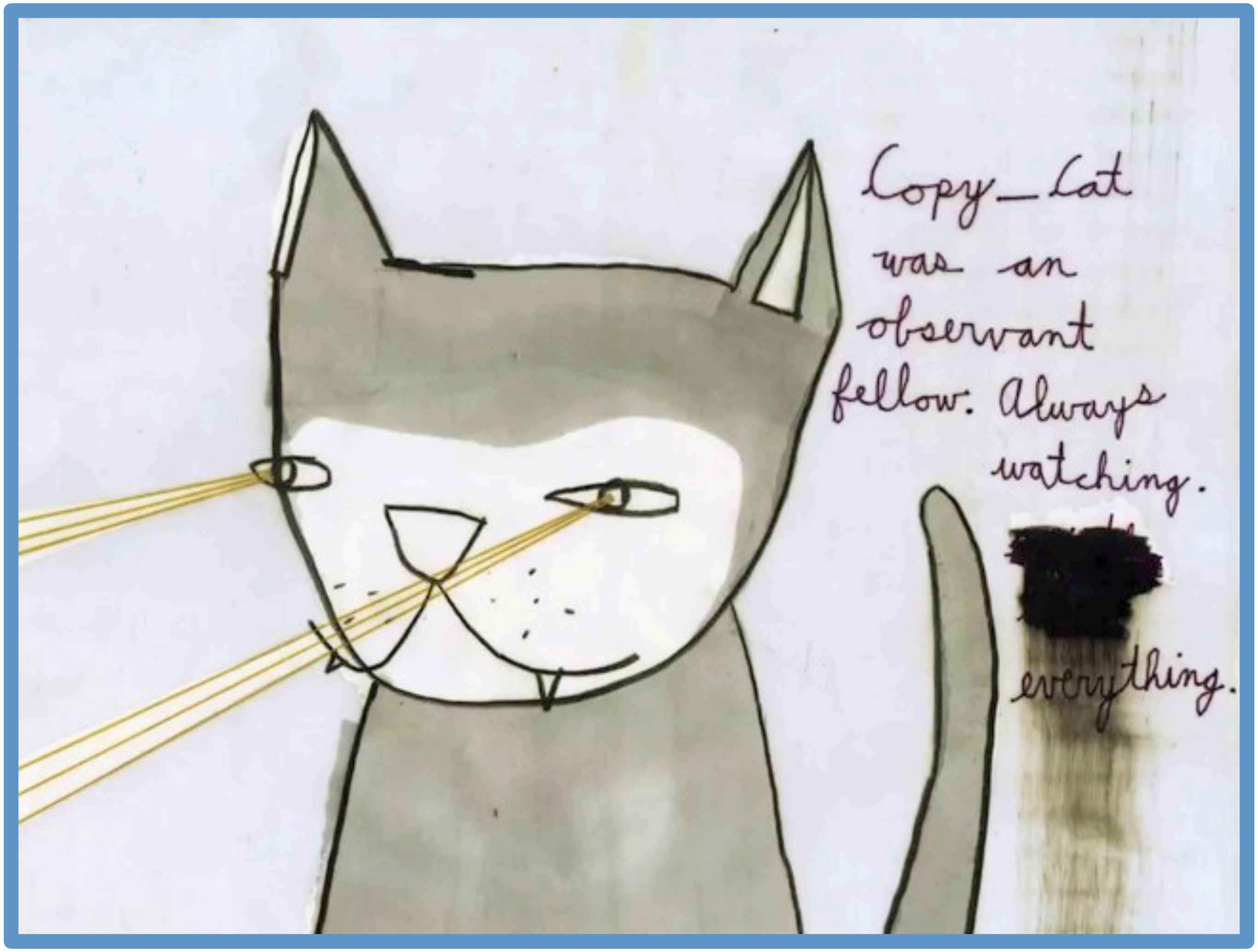
Free space optical combiner technology

- Flat on axis combiners
- Free form TIR combiners
- Curved off-axis combiners
- Arrayed or cascaded combiners

See through combiners using light guide and on-axis optics

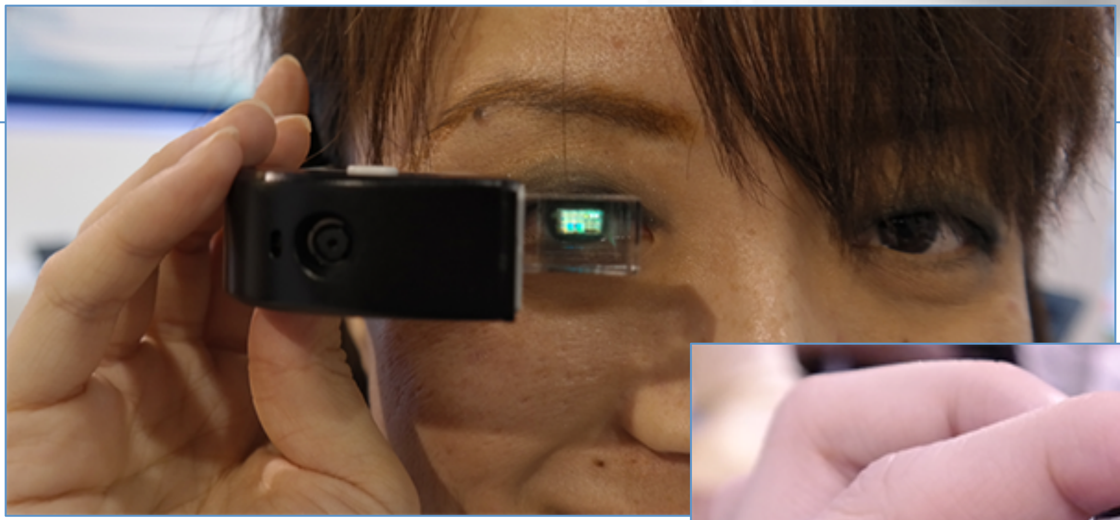
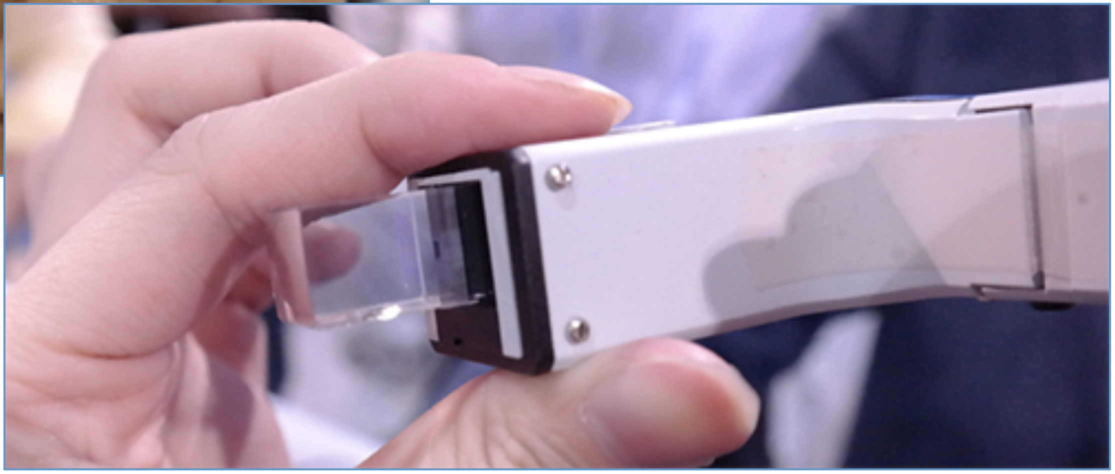
Google Glass V1:
45 degrees flat combiner in horizontal direction

Glass V1 copy-cats



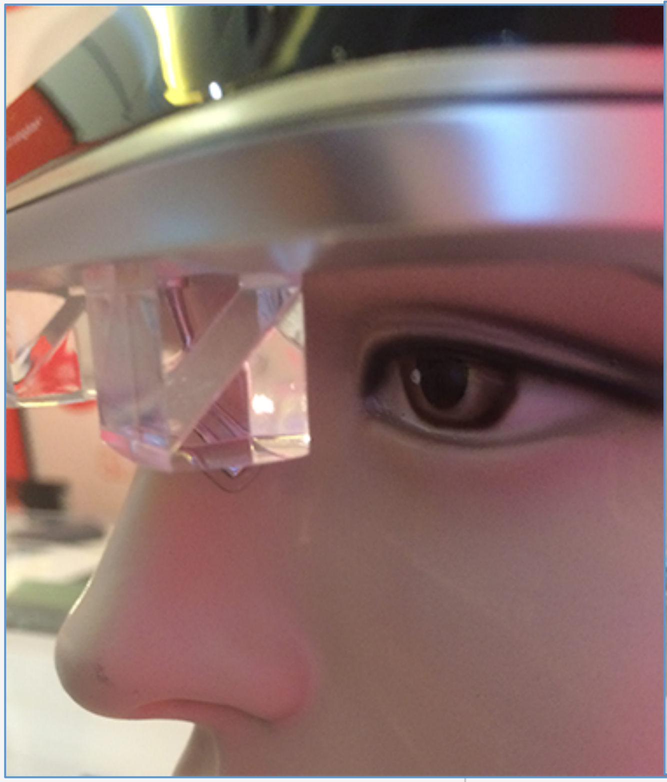
Chip Sip, Taiwan.
Identical to Glass, but larger resolution LCOS display

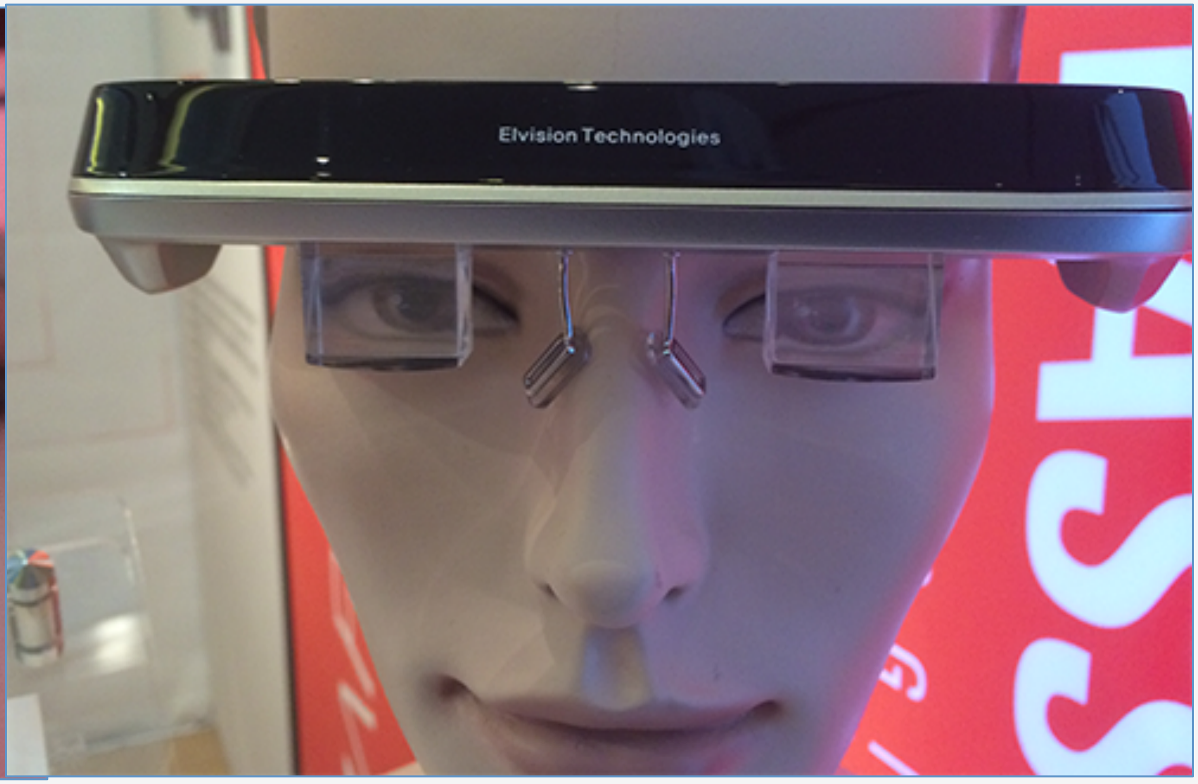


Rock Chip, Taiwan.
Uses same Chip Sip tech.
Sells glasses $500

Omnivision Santa Clara
Similar performance than Glass, higher resolution but pixels not resolved by optics.

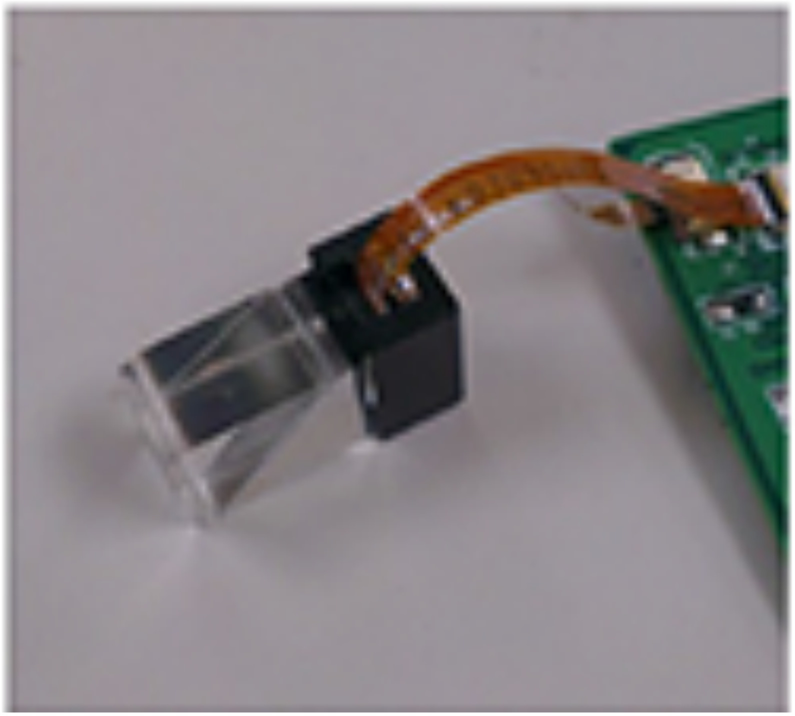


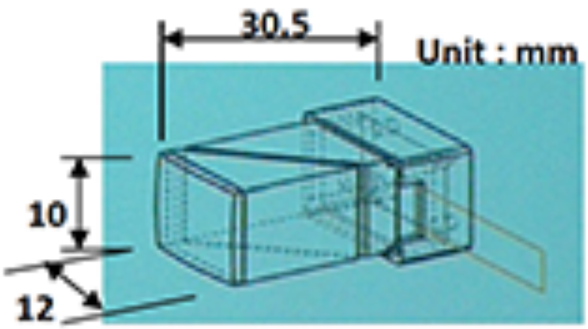


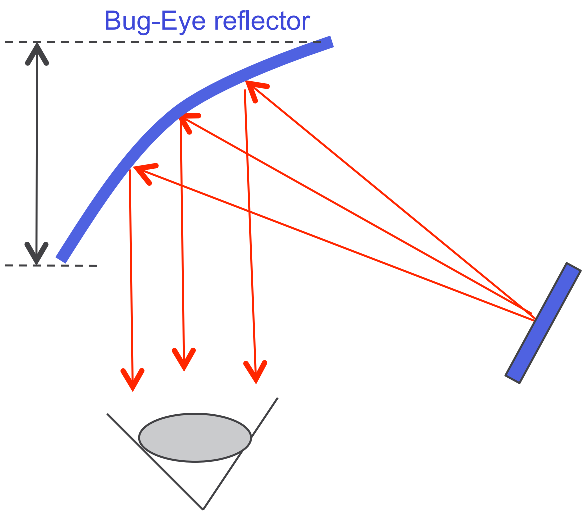
Elvision Technologies, Taiwan.
Vertical Glass architecture, uses HD OLED panel
Large FOV from large OLED microdisplay,
Large eye box from large prism / lens combiner

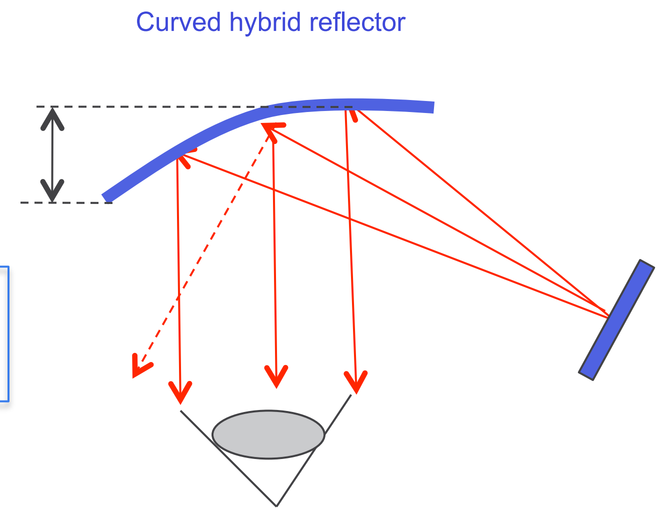
So much that classical light guide based optical display engines for HMDs are now becoming commodities much like any other consumer product

ITRI Taiwan.
Developing and selling optical engines based on reflective lens lightguide combiner and LCOS displays.









Free space optical combiner technology

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- Free form TIR combiners
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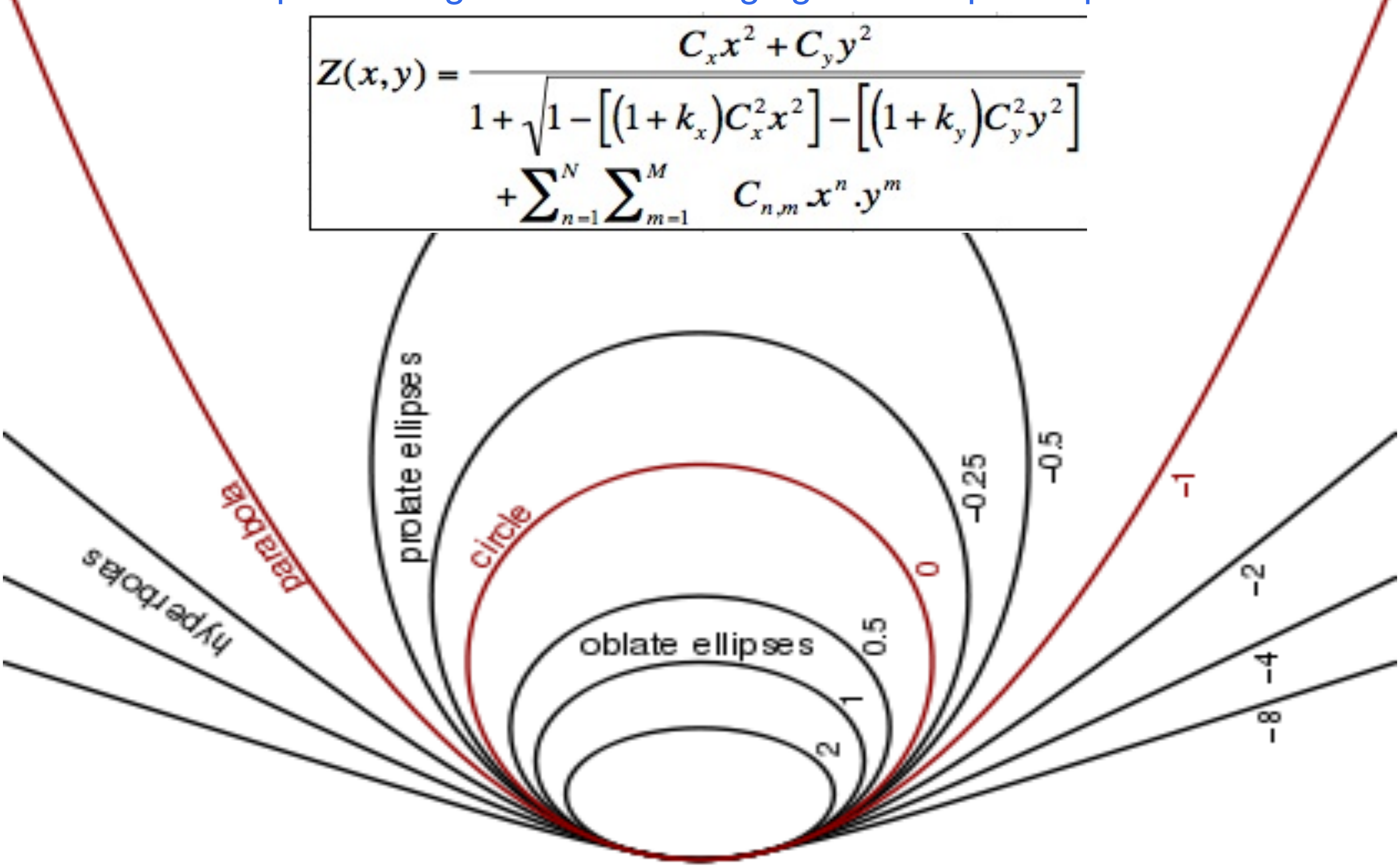
- Arrayed or cascaded combiners

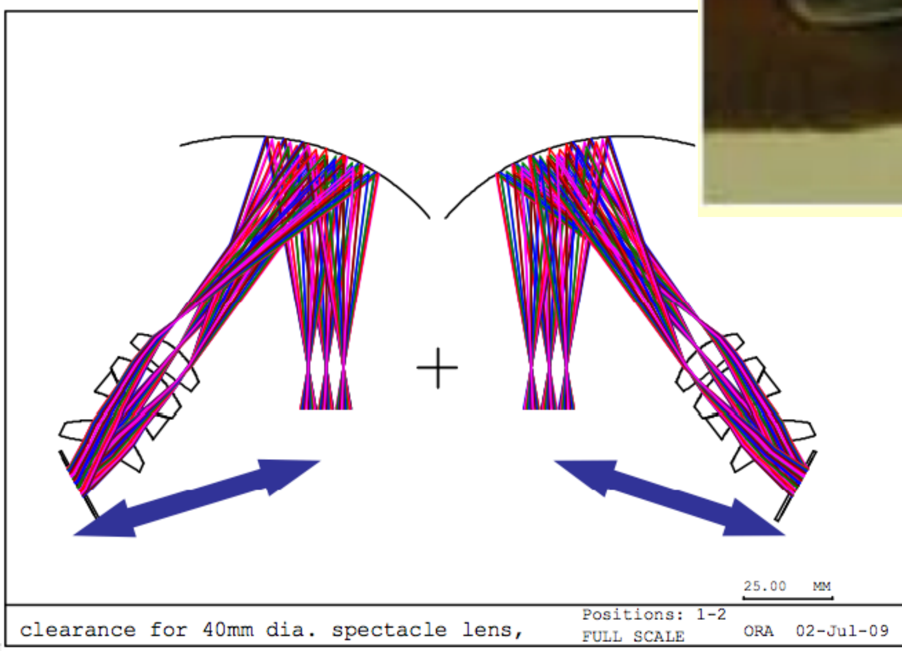
The notion of « Bug Eye » in HMD optics

Implementing the off-axis imaging task– aspheric profiles

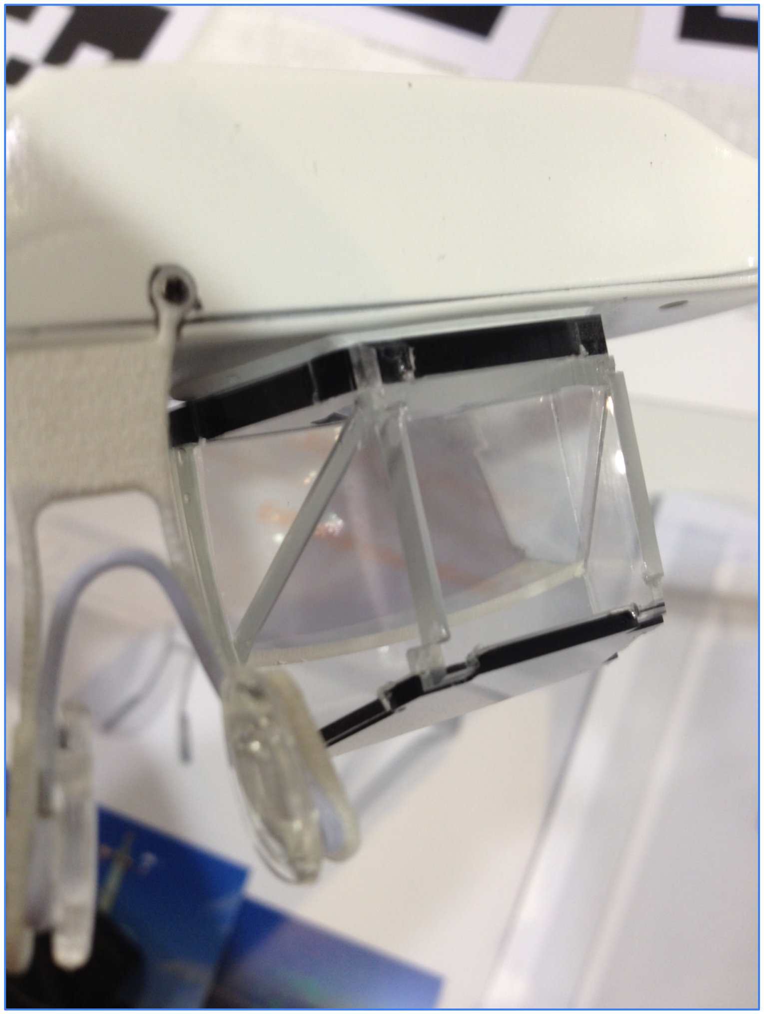
$$Z(x,y) = \frac{C_x x^2 + C_y y^2}{1 + \sqrt{1 - \left[(1+k_x)C_x^2 x^2\right] - \left[(1+k_y)C_y^2 y^2\right]}} + \sum_{n=1}^{N} \sum_{m=1}^{M} C_{n,m} x^n . y^m$$



« Bug-eye » reflective combiner – ODA Labs

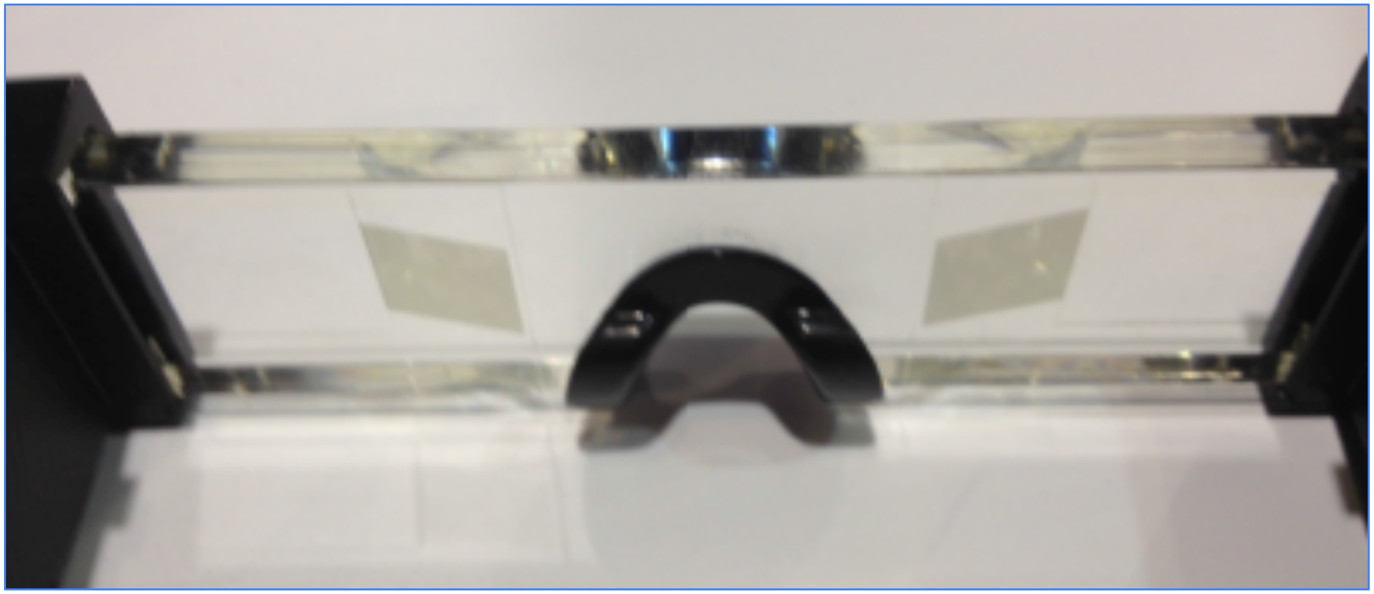


Vertical 45 degrees wide FOV combiner example (Laster)



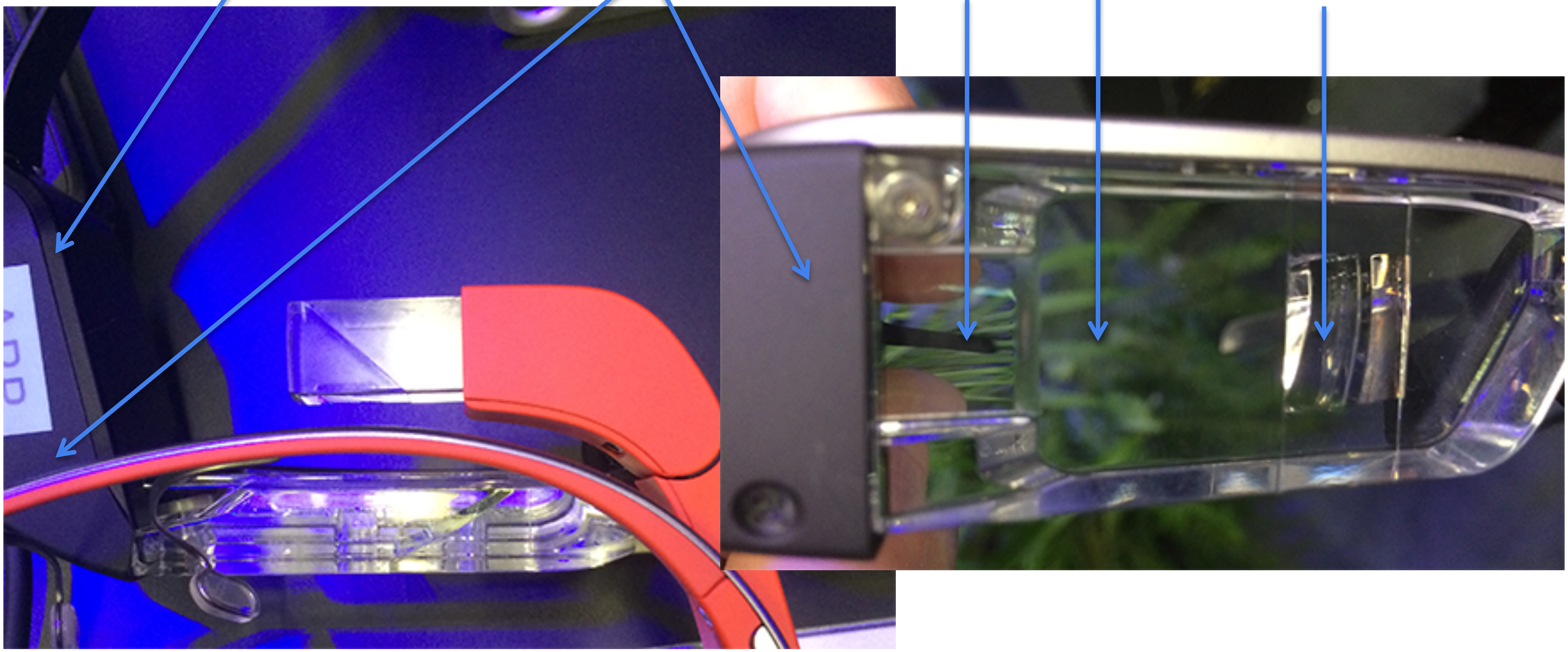
« Bug-eye » reflective combiner – Laster

Epson Moverio first gen light guide tilted mirror combiner

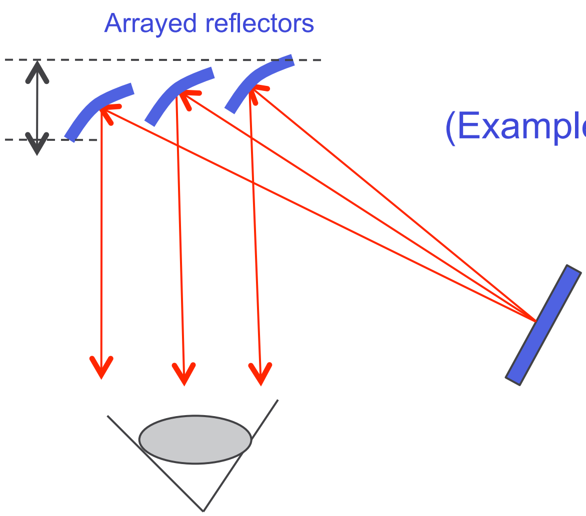


Epson Corp, Moverio BT200 (second generation)

3 collimation lenses, one prism injector, 6 TIR bounces and one curved 50/50 mirror combiner (hard coat on entire surface)



Epson Moverio BT200 (2nd gen) is as thick as Glass, but multiple times the lateral size
3 lens collimator assembly and prism injector
Eye box large, FOV large, good resolution, heavy on nose pads
… but Epson Moverio becoming the workhorse for special application developers
(engineering, research, medical, gaming…)



(Example: TTP Ltd)

Free space optical combiner technology

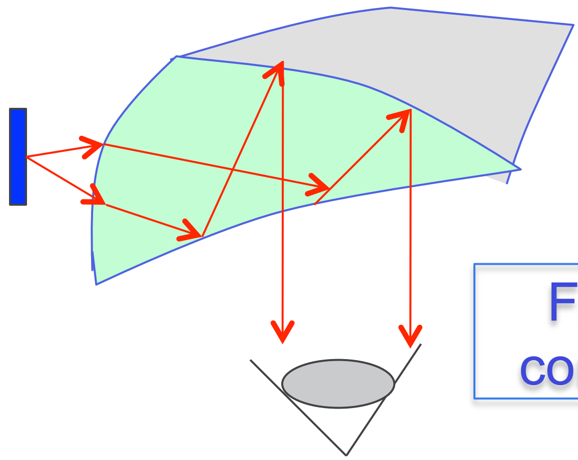
Flat on axis combiners

Free form TIR combiners

Curved off-axis combiners

Arrayed or cascaded combiners

TIR free form surfaces with see through corrector



Free space optical combiner technology

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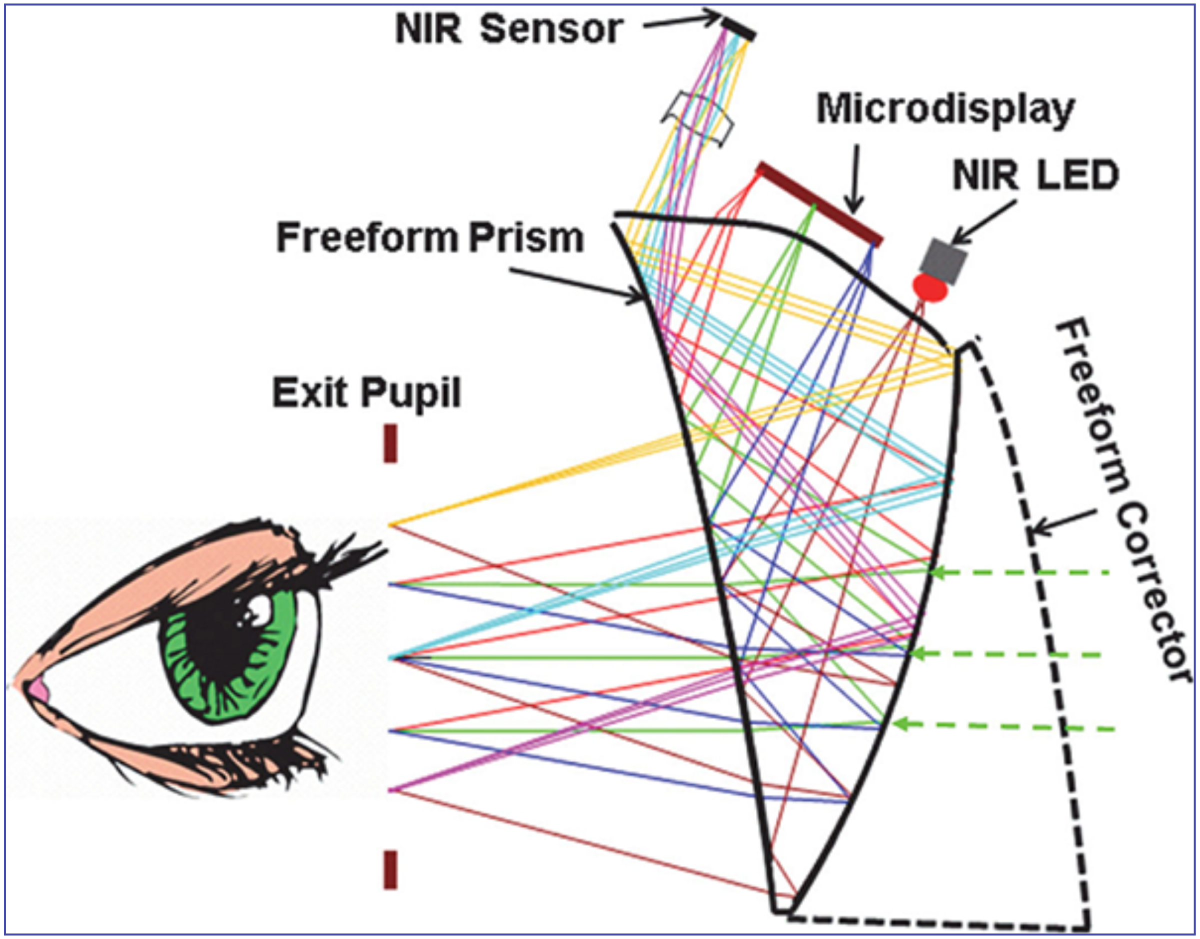
- Curved off-axis combiners
- Free form TIR combiners
- Arrayed or cascaded combiners

Example of TIR / free-form surfaces combiner



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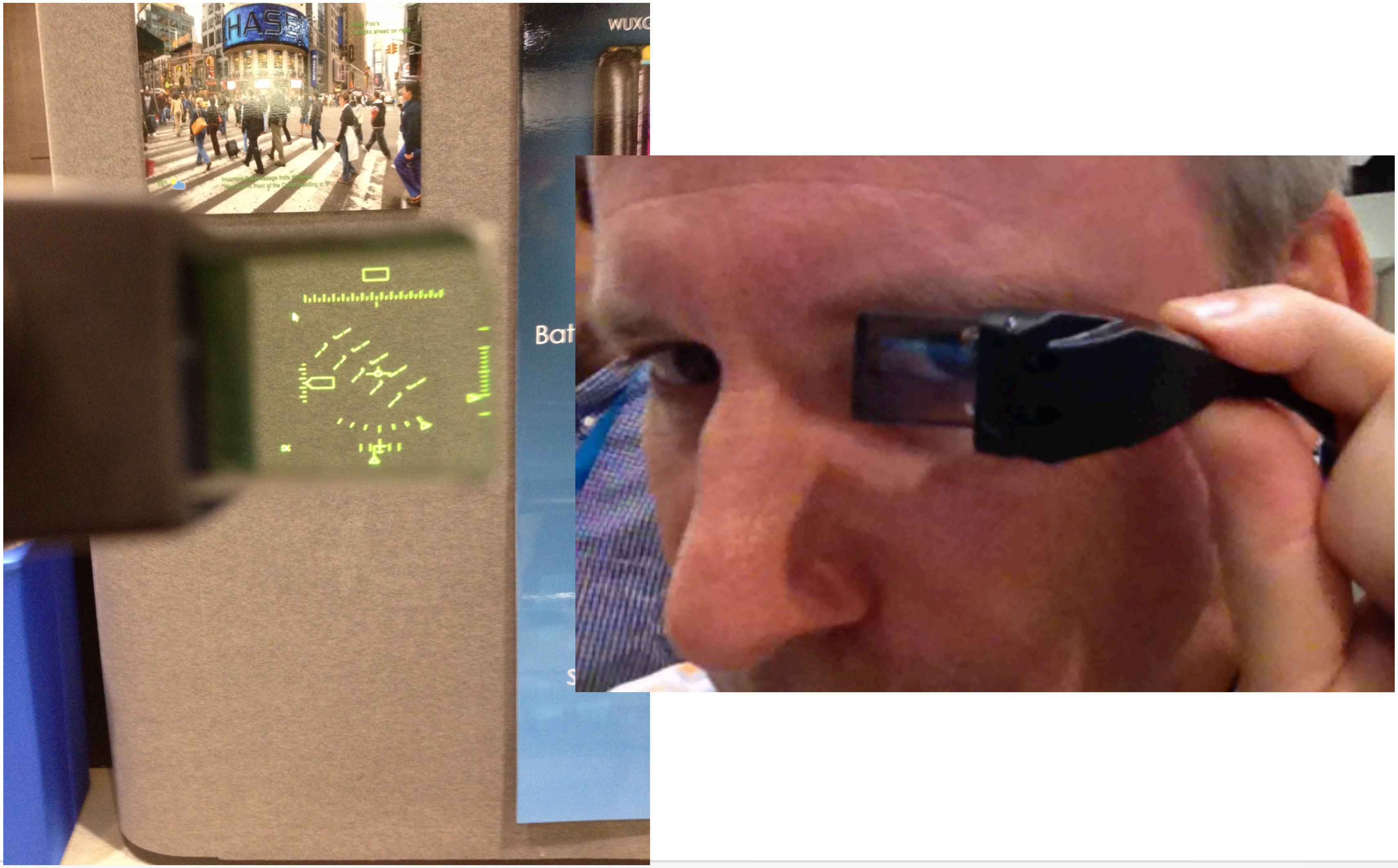
Imagine optics, monocular TIR prism combiner

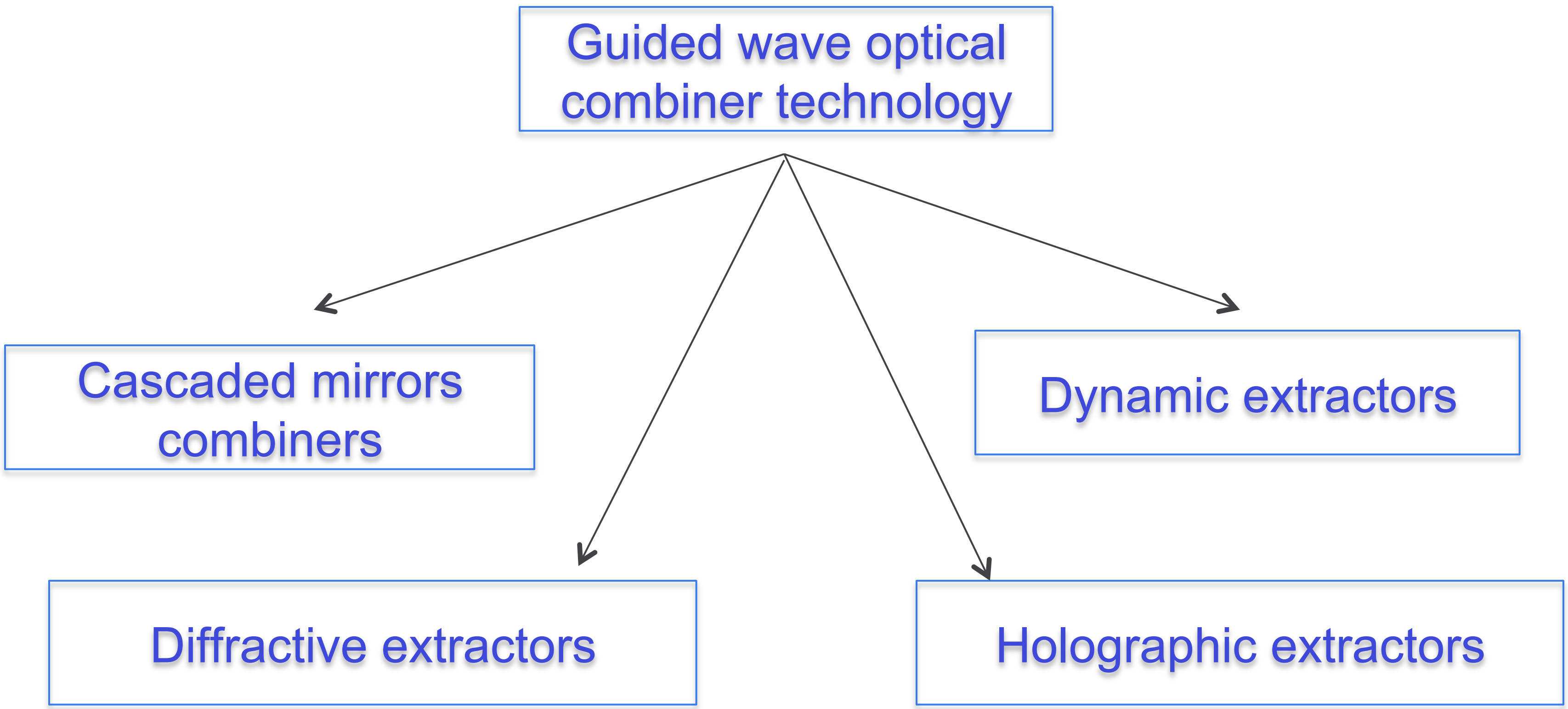


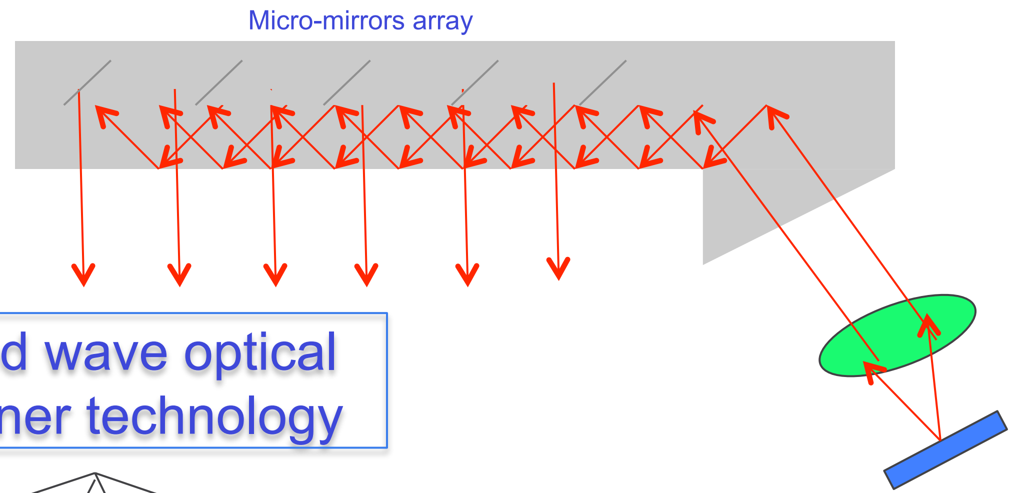
Fraunhofer binocular OLED combiner based on TIR prism

Verizon/Kopin's Golden-i, Motorola HC1 and Canon's implementations examples of TIR free-form optical combiners

Classification of optical combiners along functionalities

2- Guided wave architectures





Guided wave optical combiner technology

Cascaded mirrors combiners

Dynamic extractors

Diffractive extractors

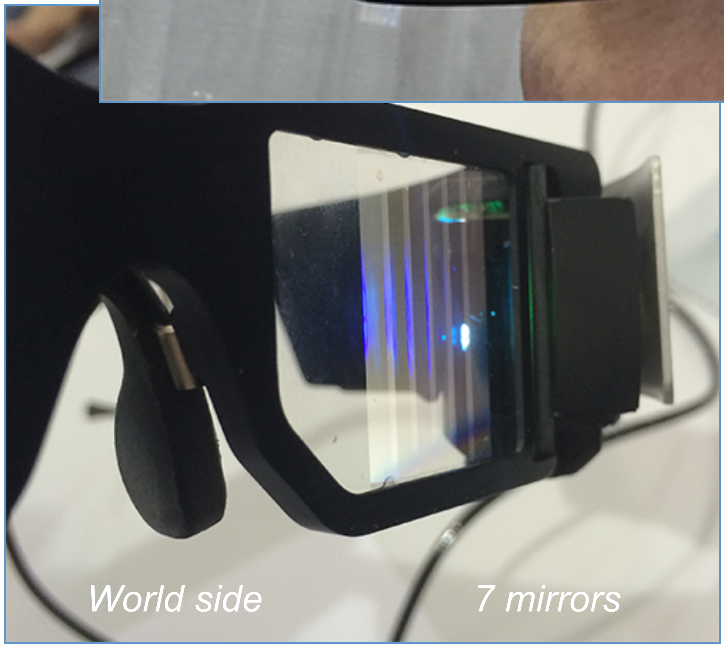
Holographic extractors

Lumus Ltd , DK40

2.0mm thick lightguide

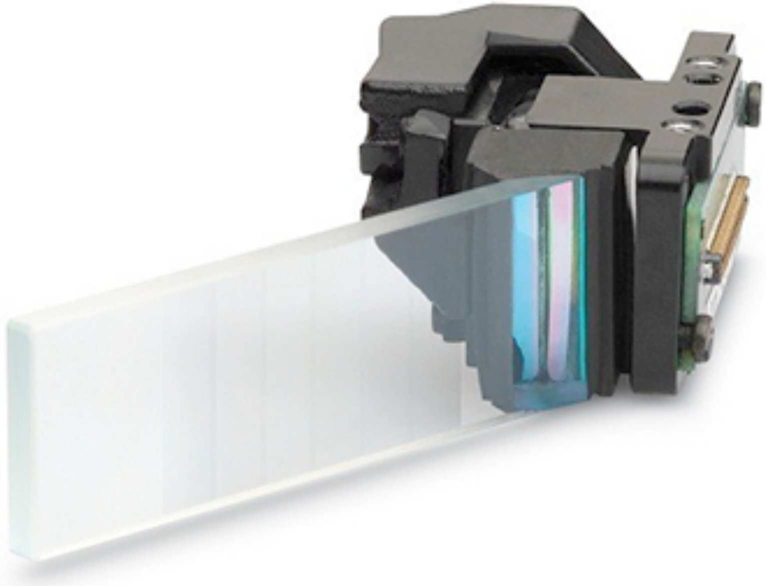
24 degrees FOV, VGA, decent eye box, decent see through, large injection port

Polarizing optics, all glass optics, difficult to produce in volume



Some world side leakage, mirrors seen under angle, injection port on the side,

Internal architecture – Lumus see through combiner



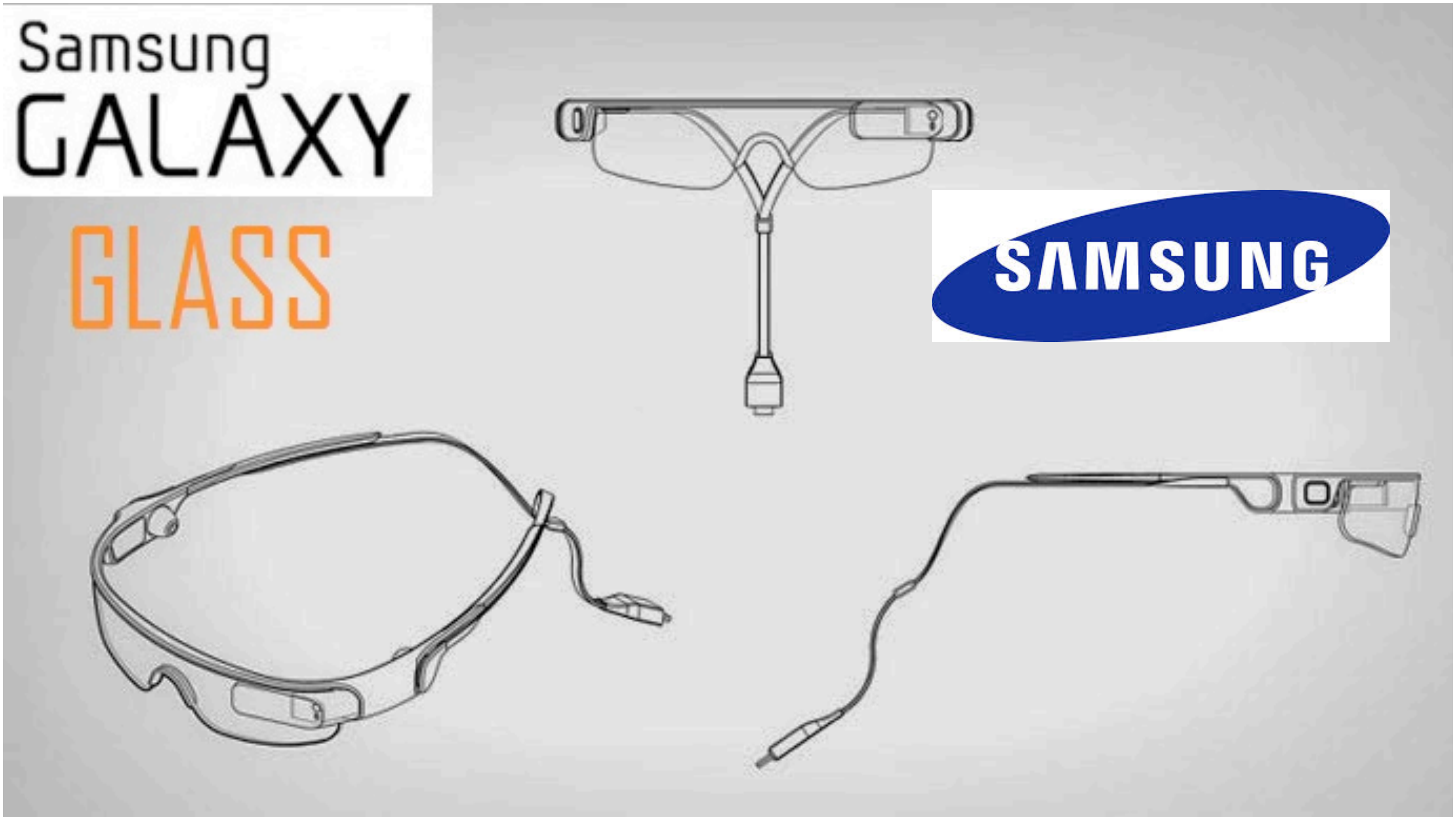
Optinvent SARL, France

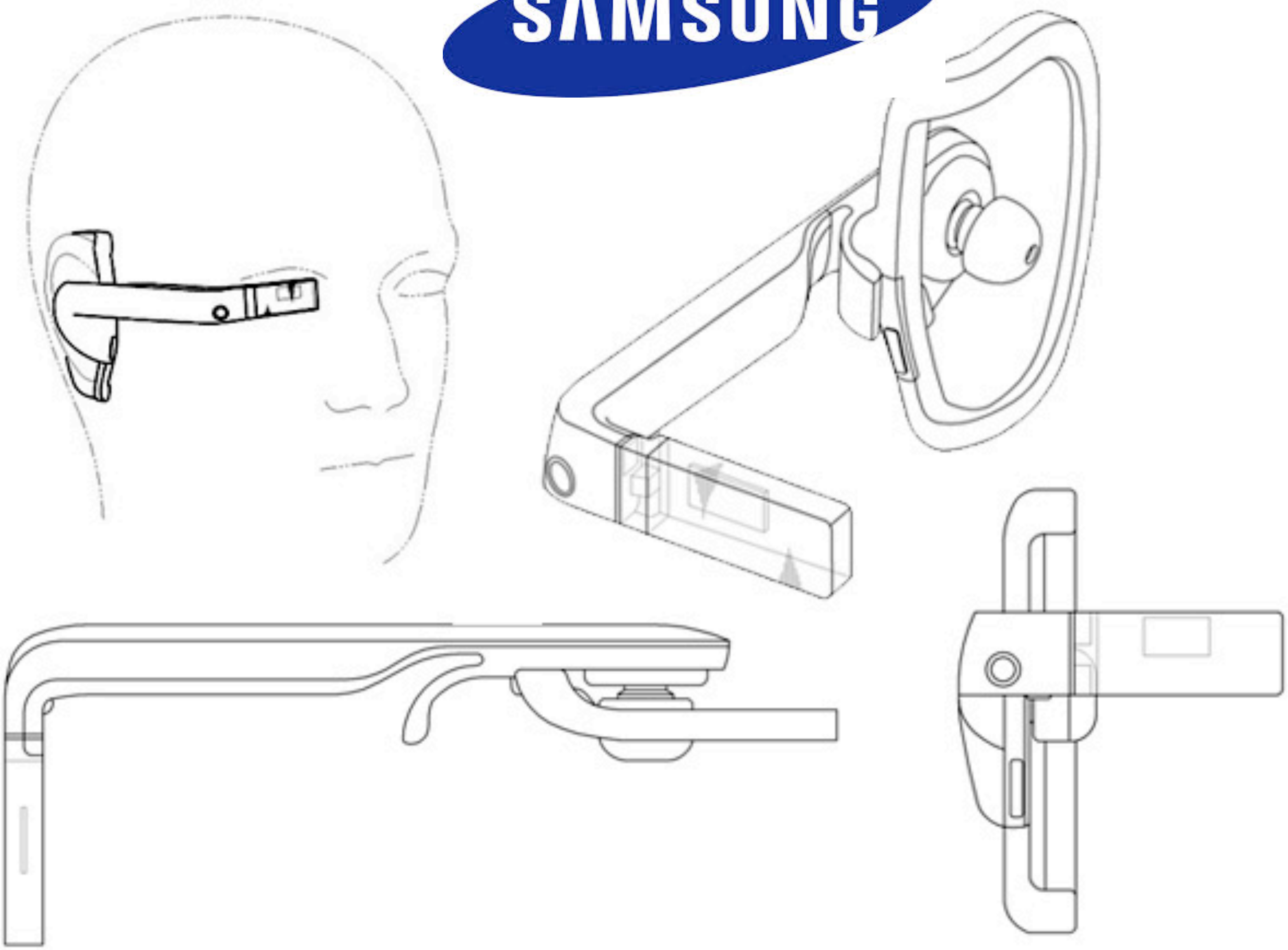
Prism array TIR lightguide (single piece injection molded in plastic for volume production)

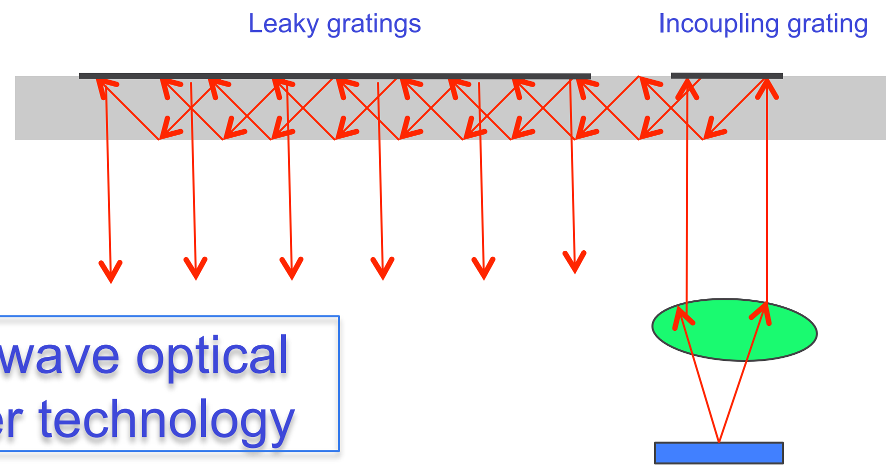
Injection port uses 3 collimation lenses and a prism injector

Relocation of VGA LCD display from up to down

See through quality similar to Lumus


Samsung
GALAXY
GLASS
SAMSUNG





Guided wave optical combiner technology

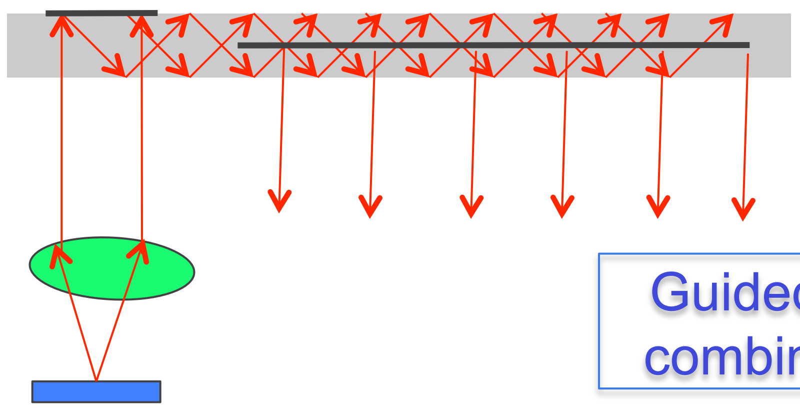
Cascaded mirrors combiners

Dynamic extractors

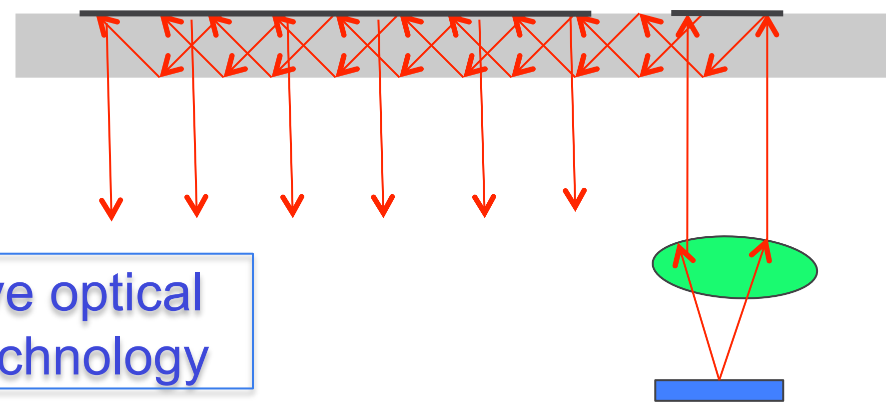
Diffractive coupler / extractors

Holographic coupler / extractors

Incoupling TIR hologram — Leaky transmission holograms



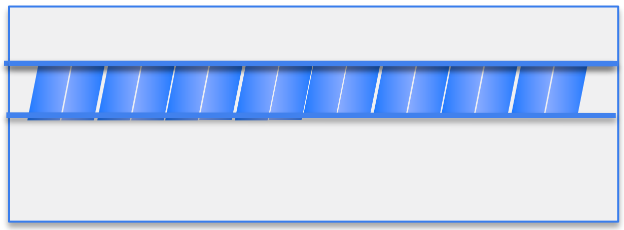
Leaky reflective holograms — IncouplingTIR hologram



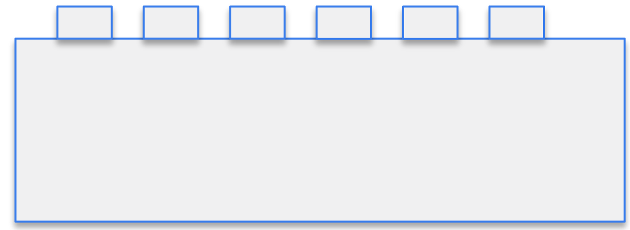
Guided wave optical combiner technology

- Cascaded mirrors combiners
- Dynamic extractors
- Diffractive coupler / extractors
- Holographic coupler / extractors

Holographic and diffractive optical elements

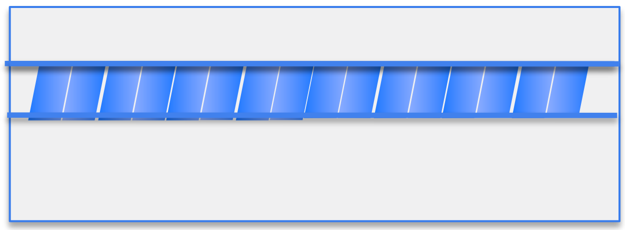


Holographic optical elements (**HOEs**)
Sanwiched “goop” with index modulation

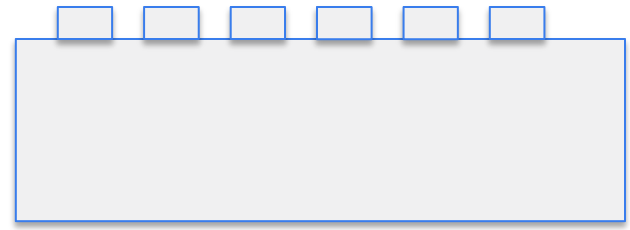


Diffractive optical elements (**DOEs**)
Surface relief modulation

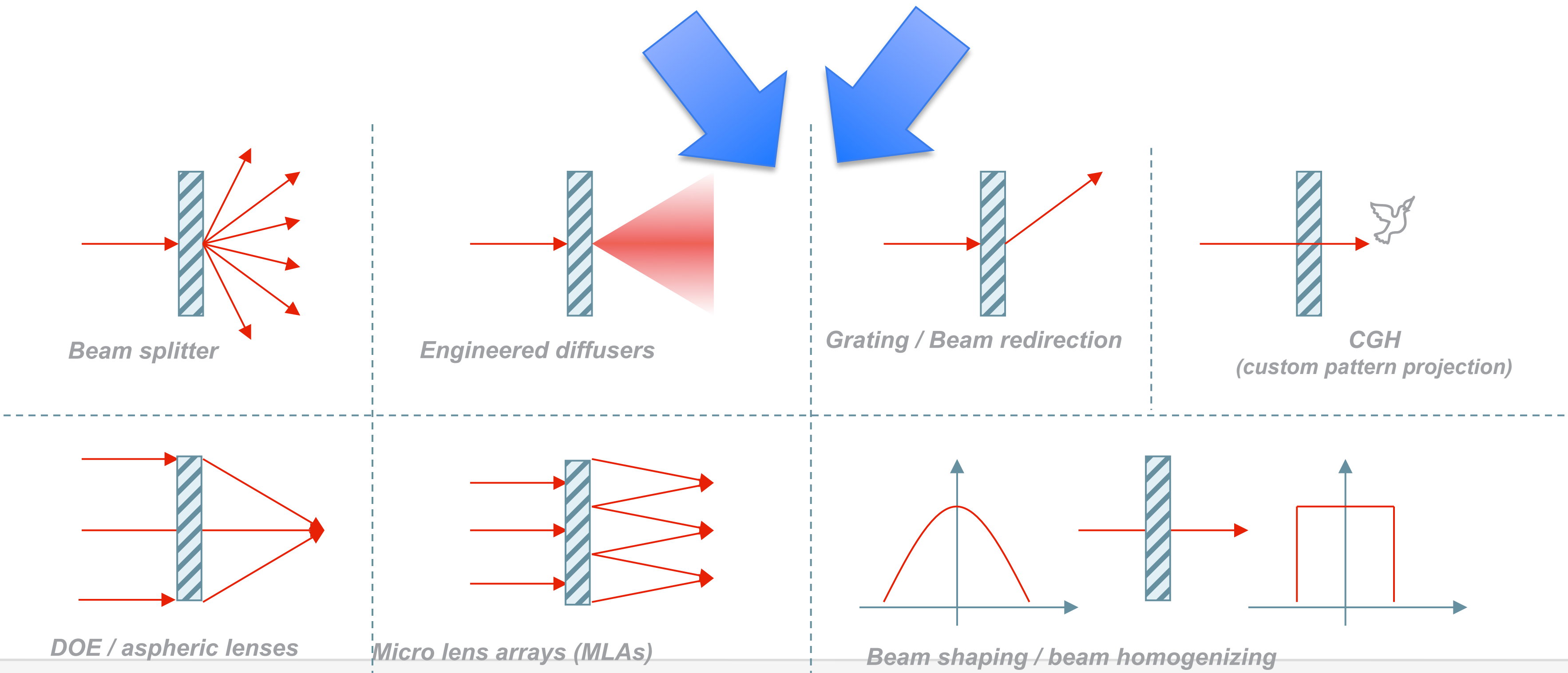
Holographic and diffractive optical elements



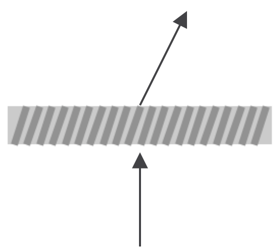
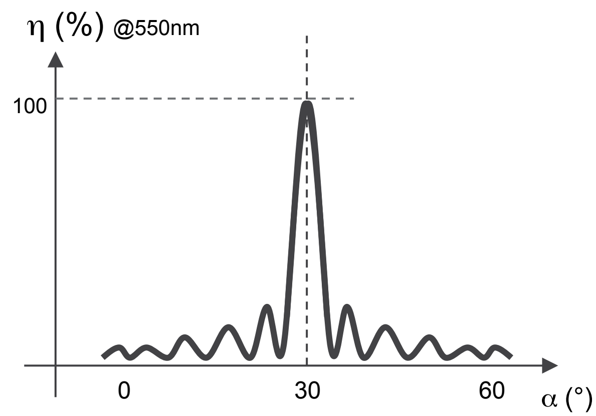
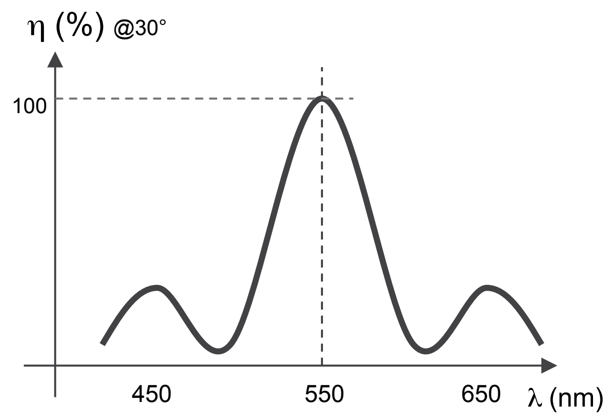
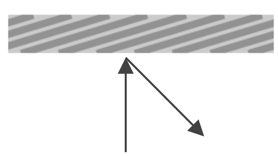
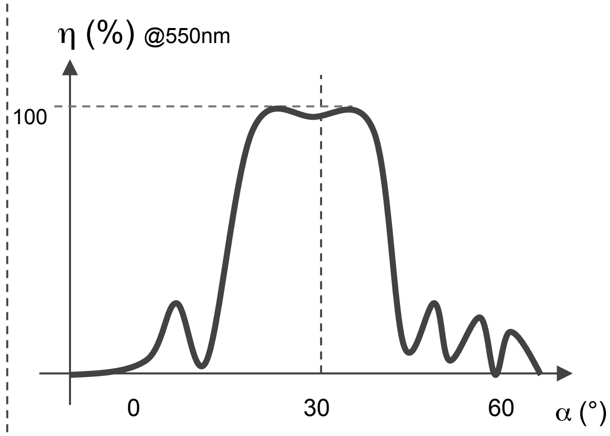
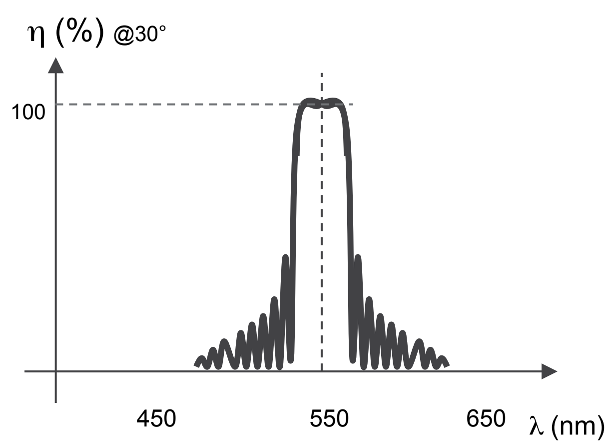
Holographic optical elements (HOEs)
Sanwiched "goop" with index modulation



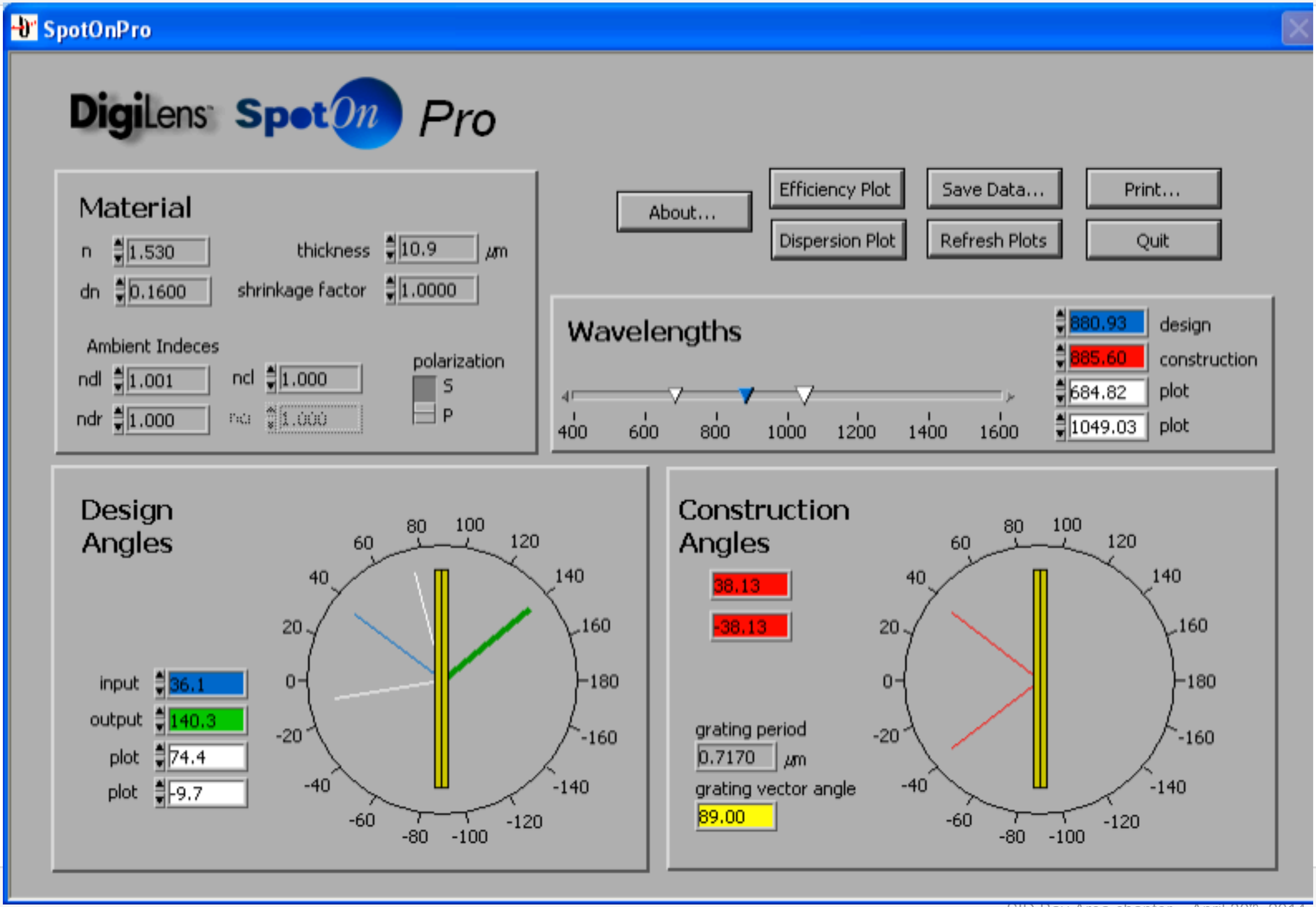
Diffractive optical elements (DOEs)
Surface relief modulation

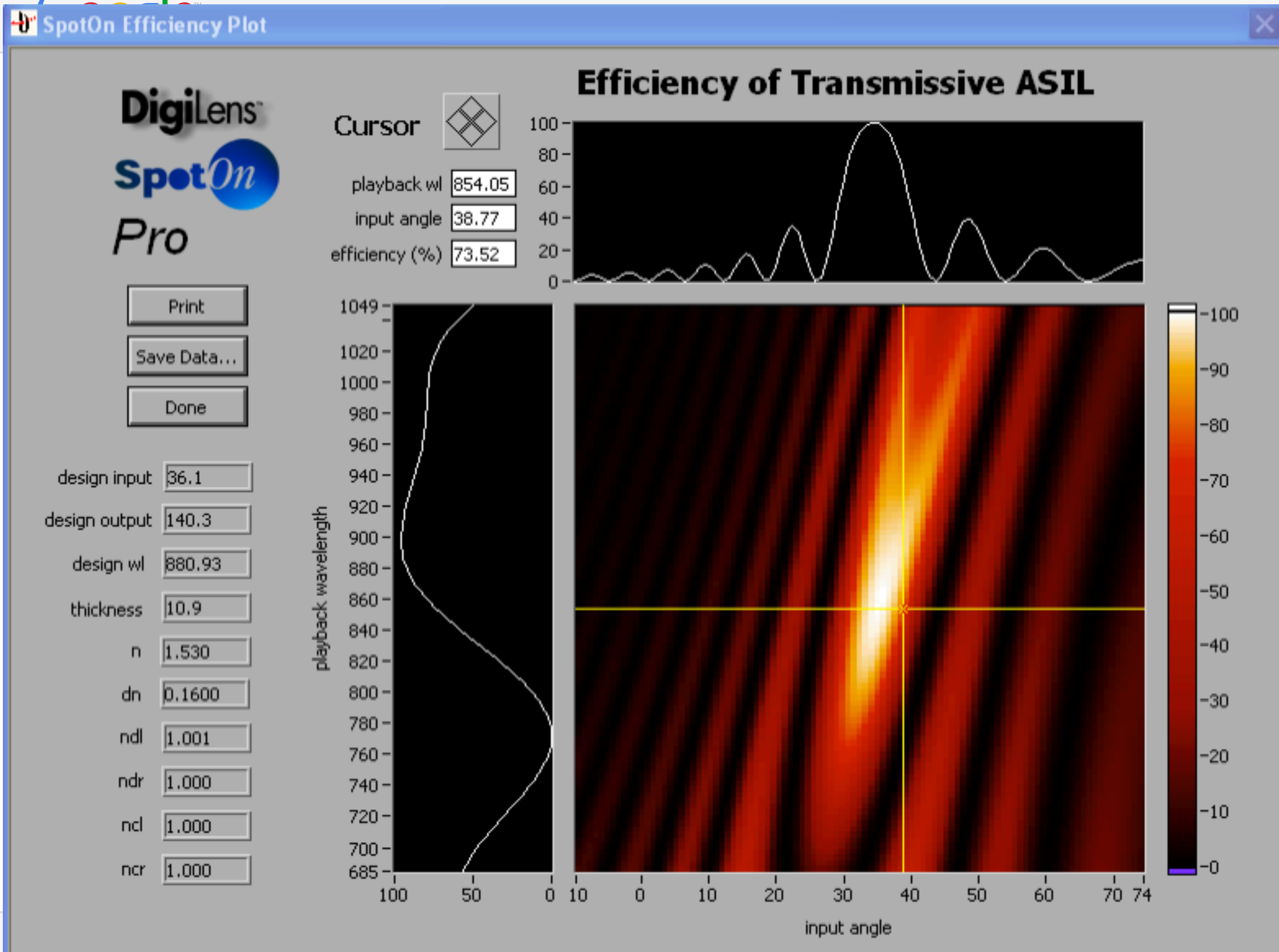


Spectral and angular Bragg selectivity in reflective and transmission volume Holograms

Hologram type	Angular selectivity	Spectral selectivity
Transmission hologram 		
Reflection hologram 		

Kogelnik model for Bragg selectivity in volume holograms



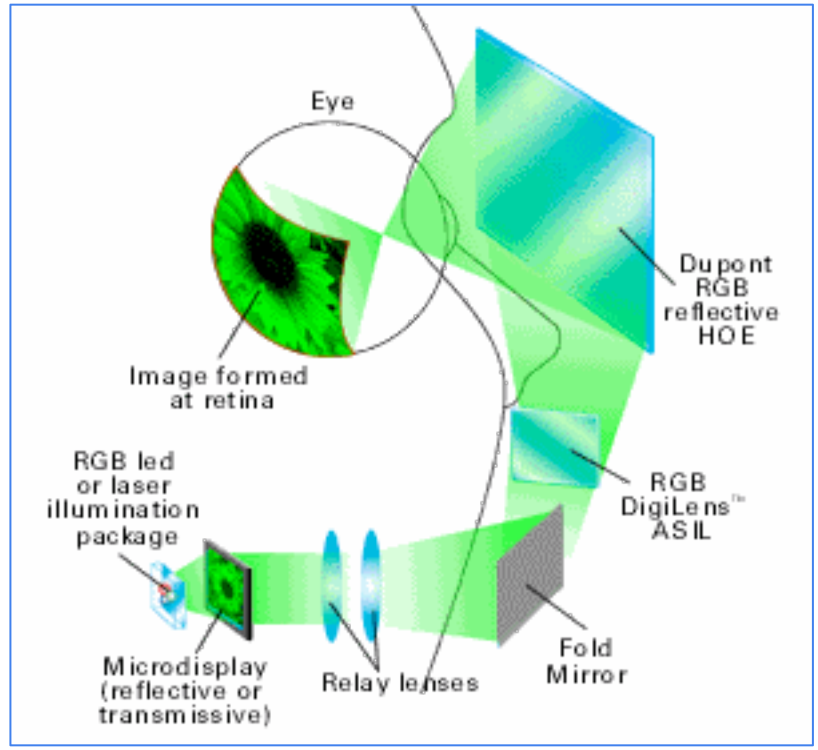


SpotOn Efficiency Plot
DigiLens
SpotOn
Pro
Print
Save Data...
Done
design input 36.1
design output 140.3
design wl 880.93
thickness 10.9
n 1.530
dn 0.1600
ndl 1.001
ndr 1.000
ncl 1.000
ncr 1.000
Cursor
playback wl 854.05
input angle 38.77
efficiency (%) 73.52
Efficiency of Transmissive ASIL
playback wavelength
input angle

Google

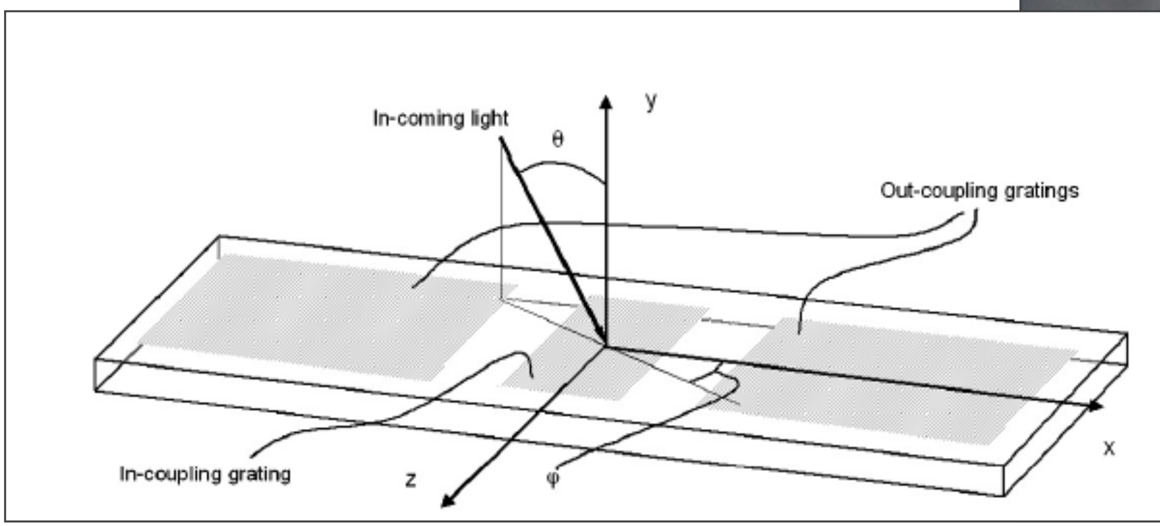
Digilens / SBG Labs examples of curved reflector or planar holographic combiners

DigiLens®

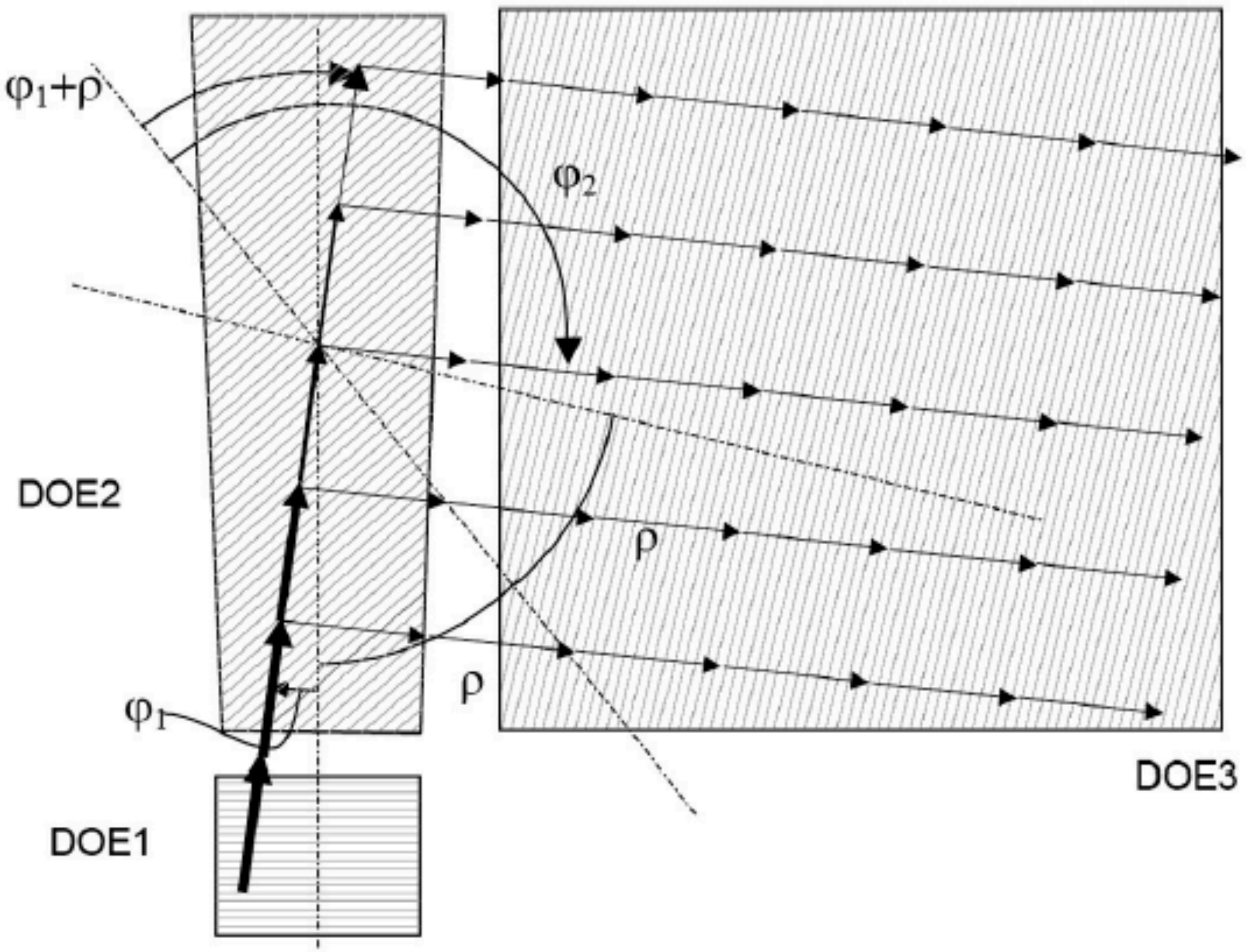


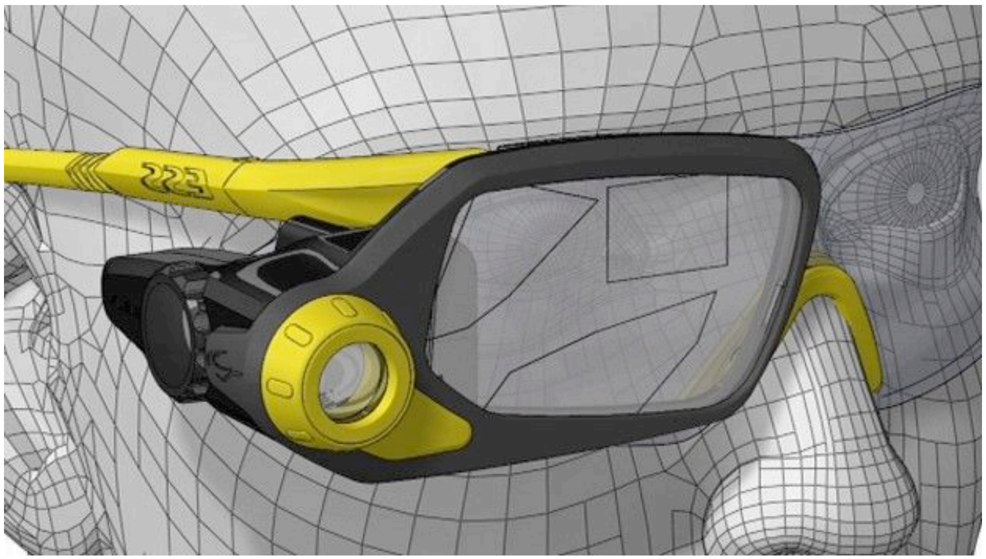
Google

Vuzix / Nokia Waveguide diffractive combiner (with laser pico projector)



Example of Exit Pupil Expander in 2 directions





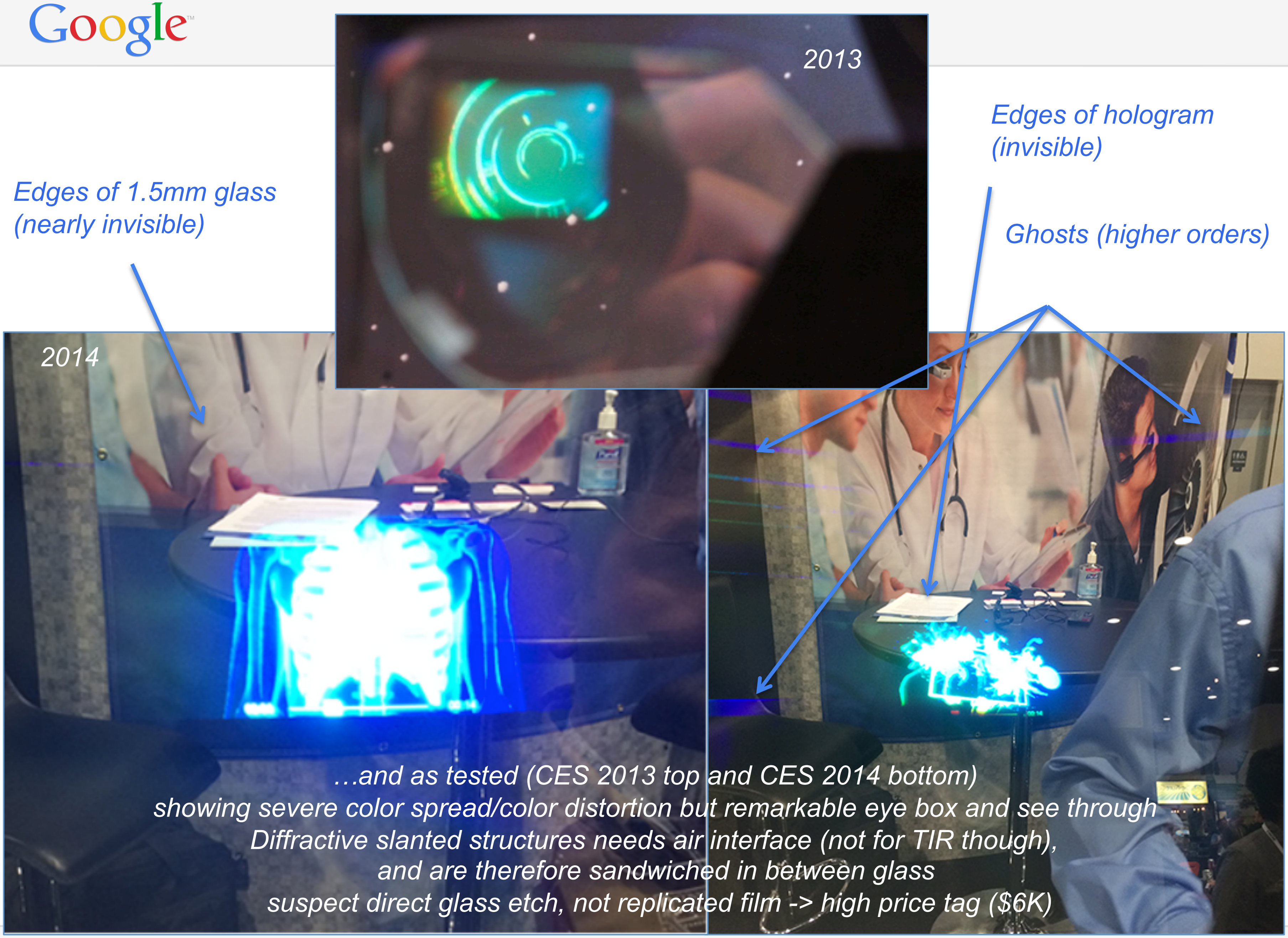
Vuzix Inc. M2000AR
Waveguide diffractive combiner with two exit pupil expanders (diffractive also)
Large injection port but large eye box thanks to EPEs,
“full” color (lots of color spread), uses laser sources (pico projector)

Google

Edges of 1.5mm glass (nearly invisible)

Edges of hologram (invisible)

Ghosts (higher orders)

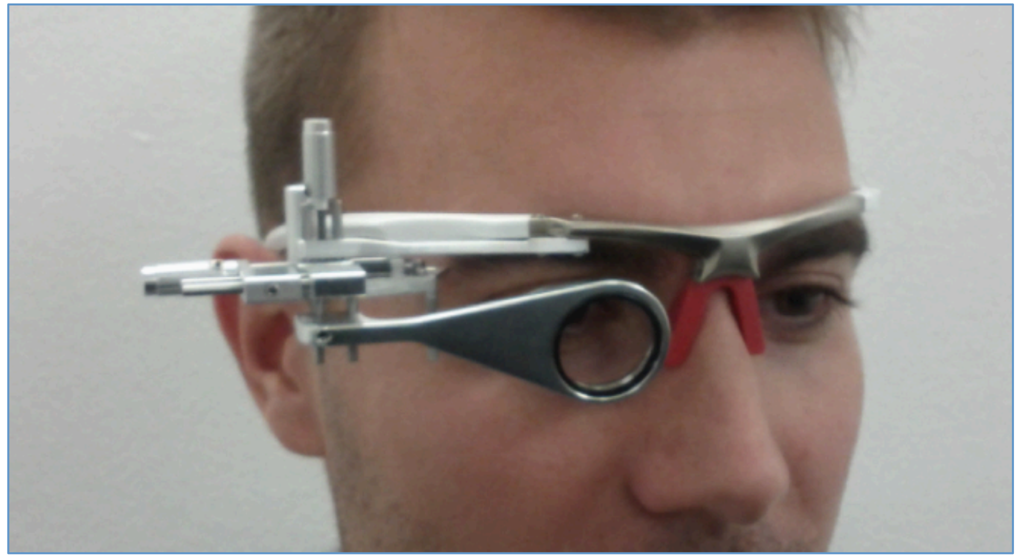


…and as tested (CES 2013 top and CES 2014 bottom)
showing severe color spread/color distortion but remarkable eye box and see through
Diffractive slanted structures needs air interface (not for TIR though),
and are therefore sandwiched in between glass
suspect direct glass etch, not replicated film -> high price tag ($6K)

Google

Last year

Now



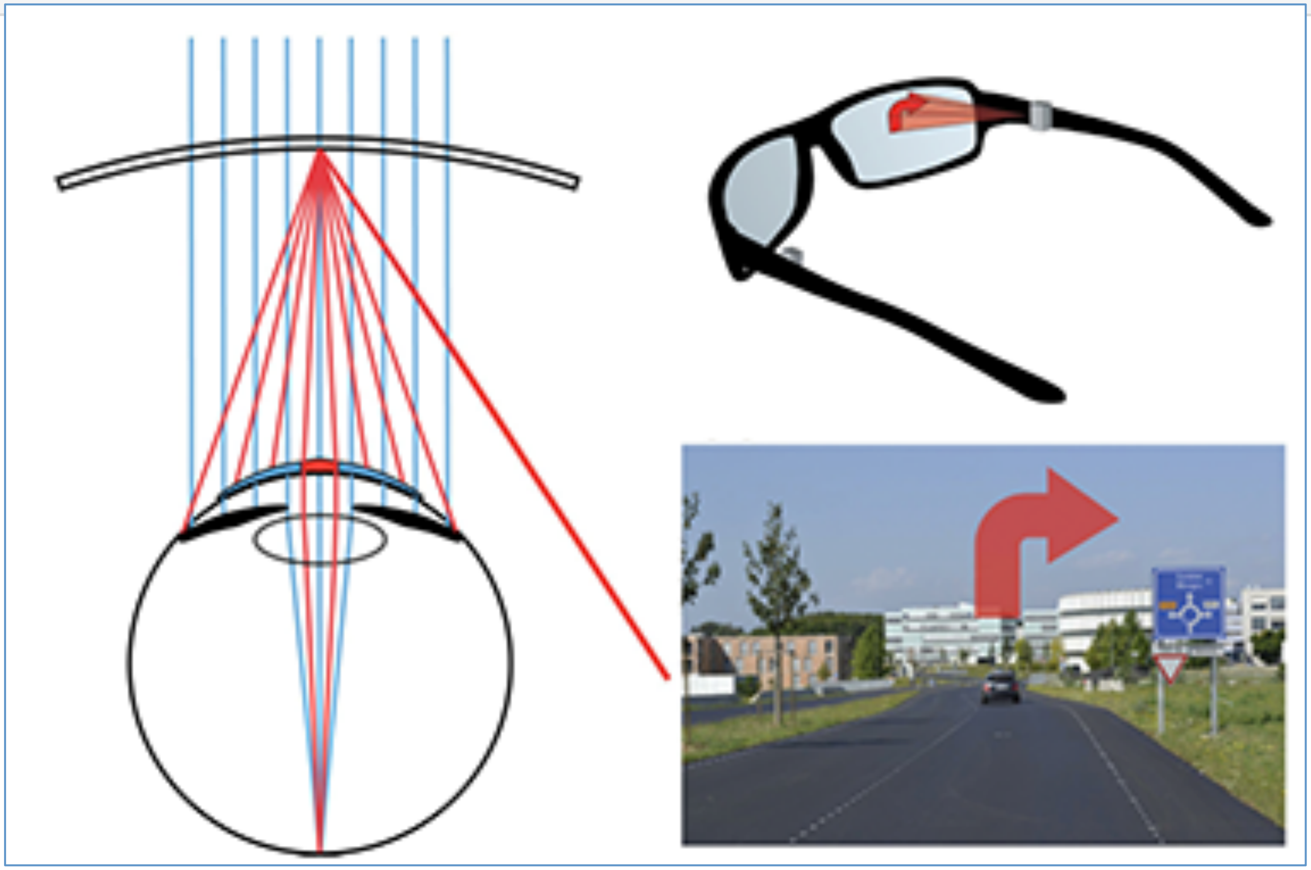
Maybe one day…

Glass up

Free-space diffractives

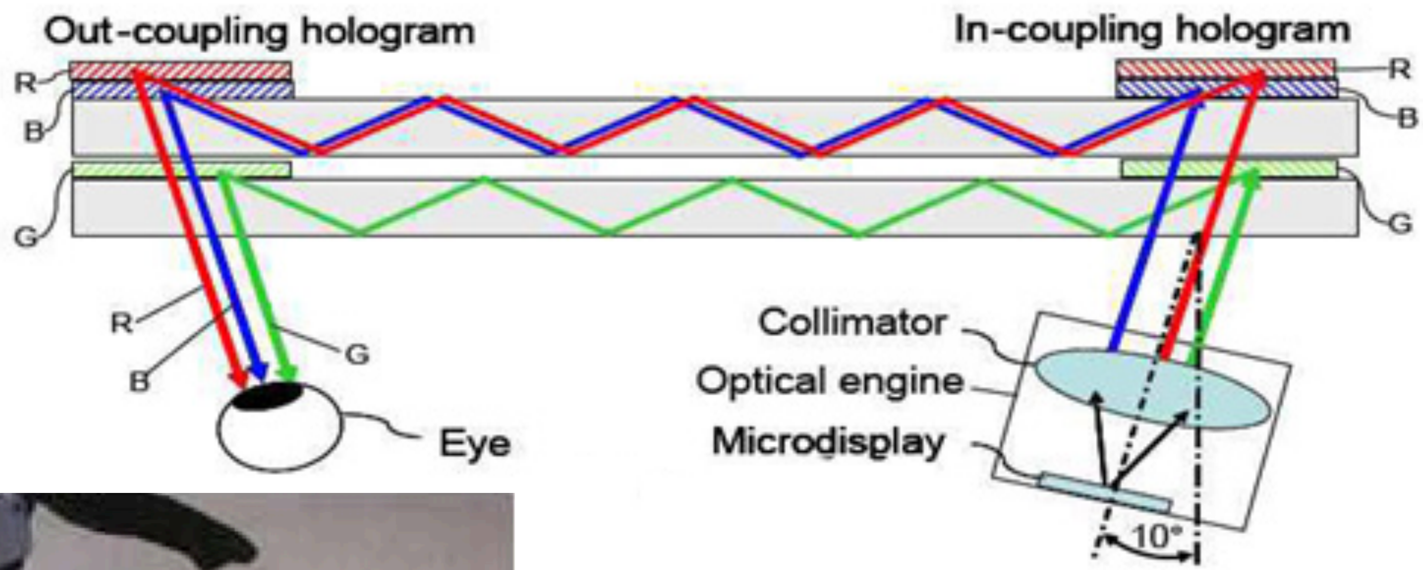
Italian flair with "Glass up"

Ultra small eye box, singe color

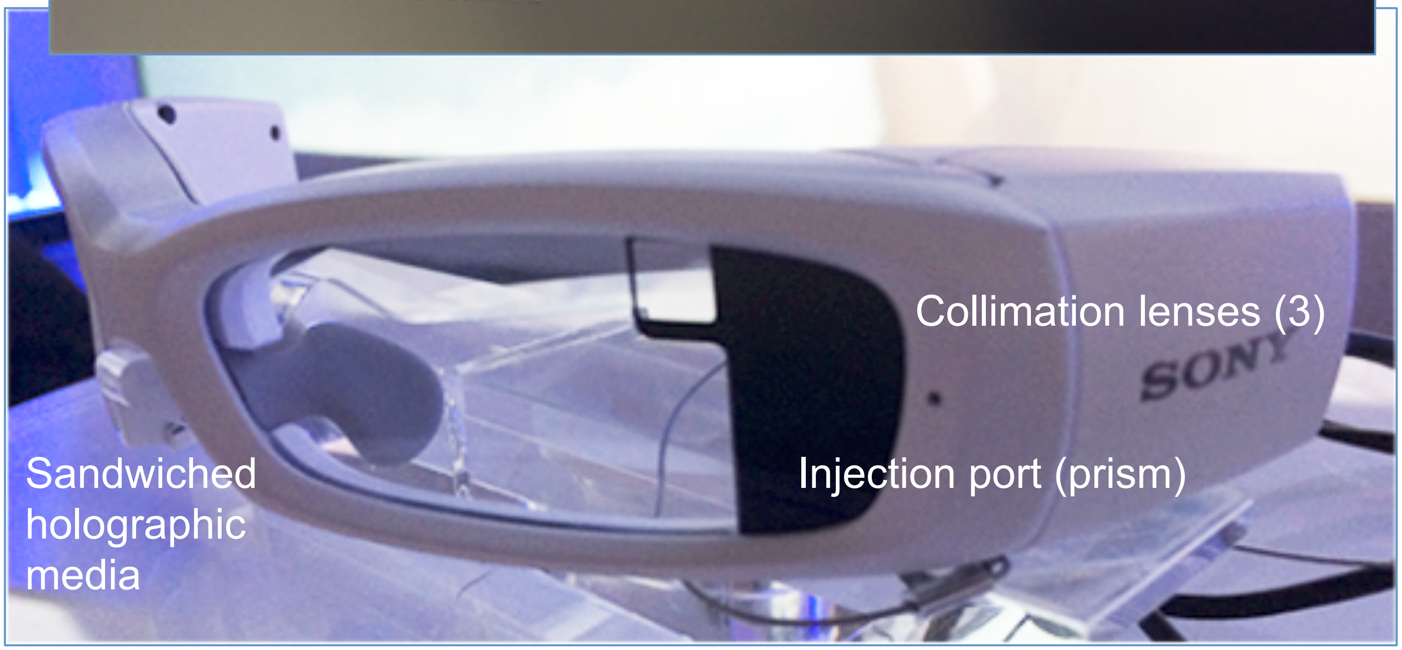


Composyt Labs Lausanne (CH)
Volume reflective hologram (Bayer photopolymer material)
recorded directly on curved base surface of Rx lens
Unlike Sony, free space hologram does not require air interface (no TIR)
But Hologram is directly on inner surface, not protected from scratches, environment, etc…

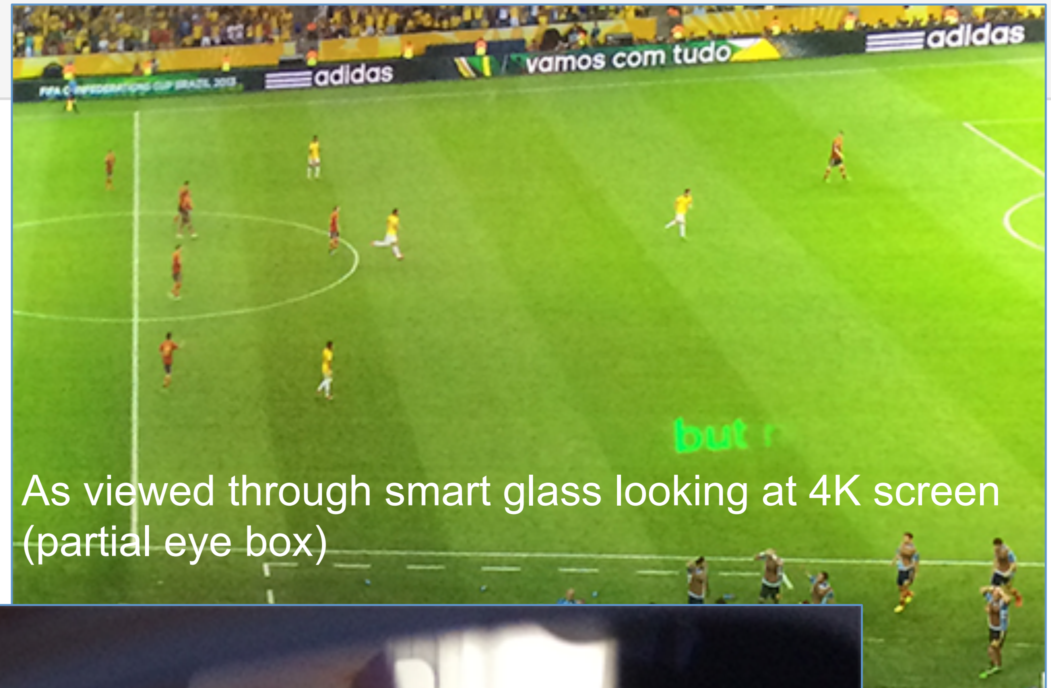
Example of SONY reflective holographic combiner

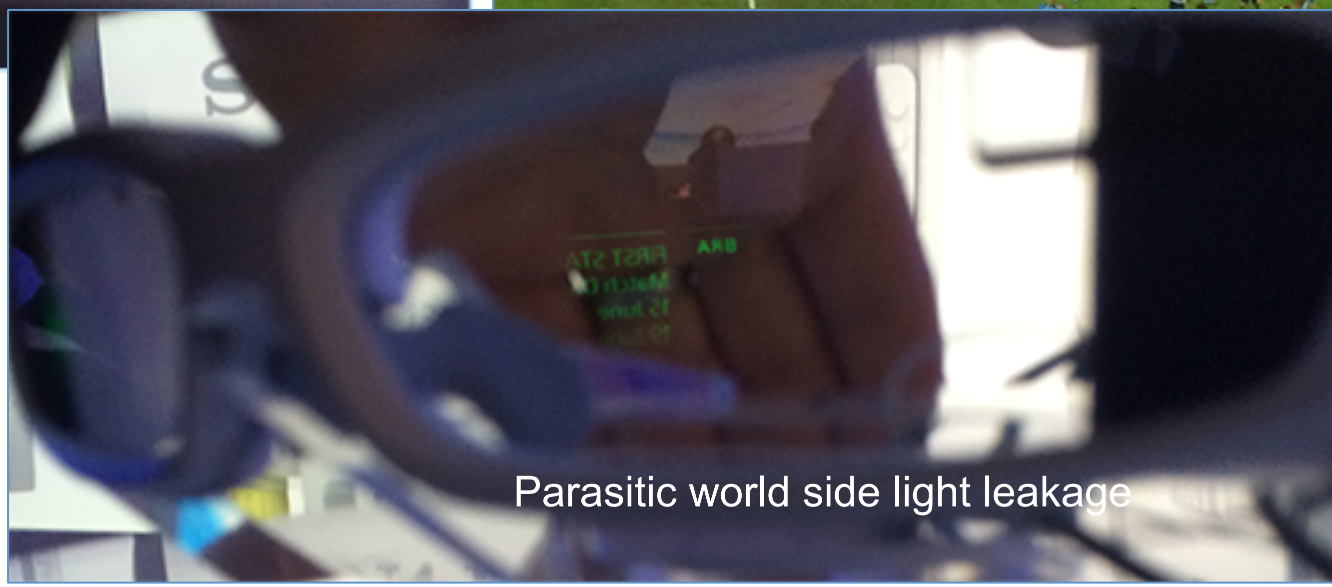


Uses guided space and super-imposed RGB reflective volume holograms.
Horizontal design.



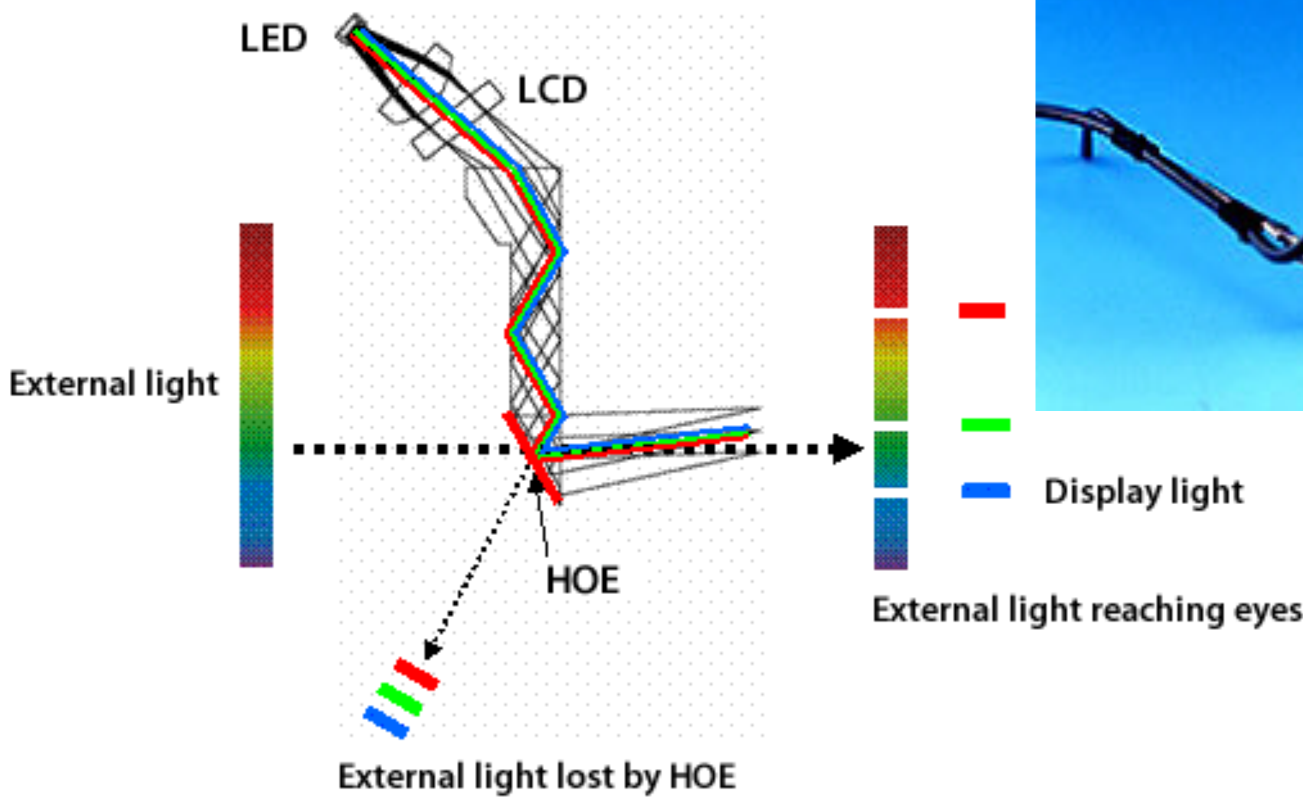
Sony Ltd. Japan
Holographic waveguide combiner (DNP Photopolymer)
Single color, sandwiched in between glass plates
Marketed by Sony only as subtitle glasses to be used indoor
(problem with environmental sensitivity of holographic goop? - temp, UV, humidity…)

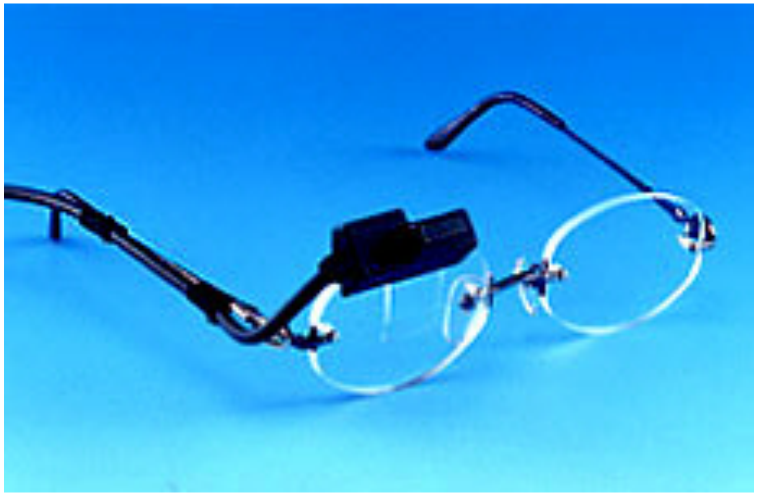




Low resolution, single color, small eye box but large FOV, some world side leakage, relies on TIR thus requires air gaps if inserted in prescription lenses

Example of KONICA/MINOLTA volume holographic combiner

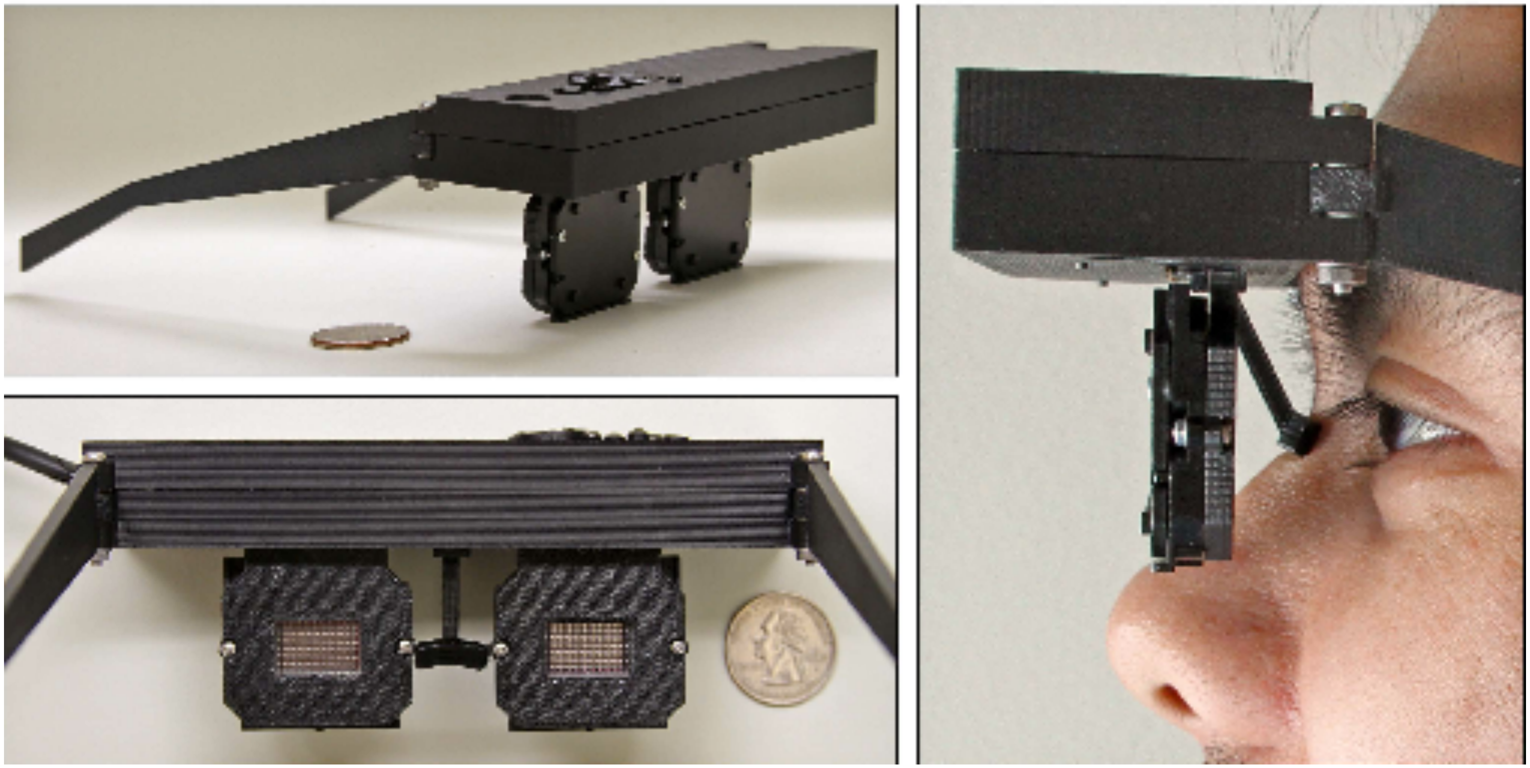




Uses guided space and single reflective hologram with multiple RGB exposure. Vertical design.

… and a few odd balls which cannot be classified

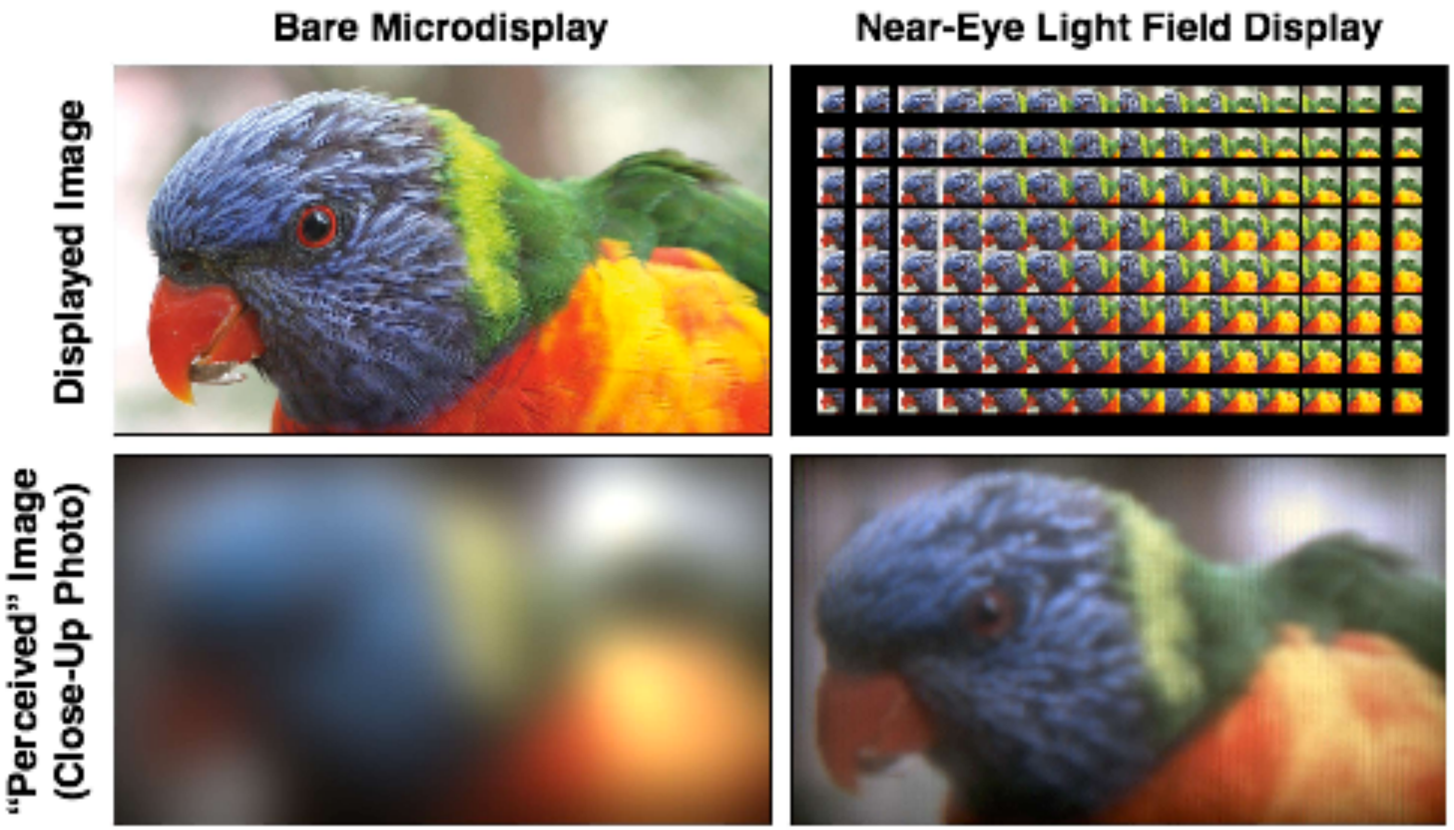
NVIDIA Research, Santa Clara
Light Field Near to Eye Display

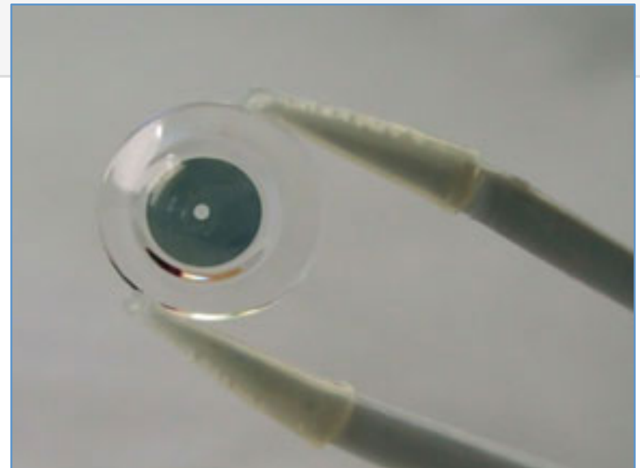


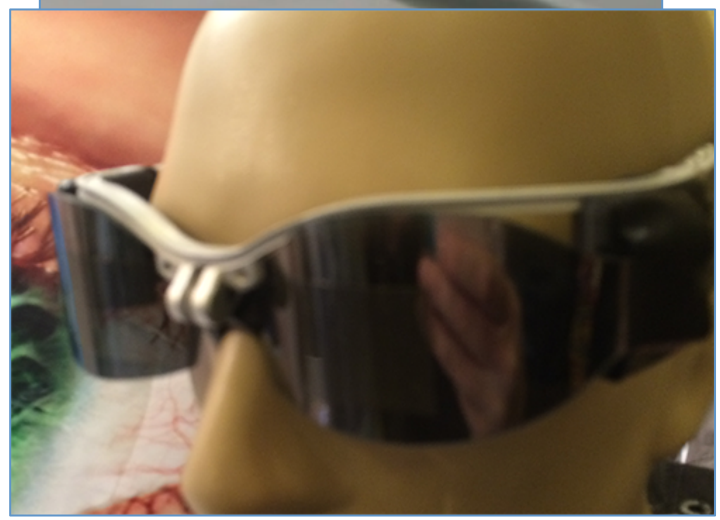
Implemented in binocular mode, by viewing an OLED microdisplay, depicting interlaced perspectives, through a microlens array.
Addressing accommodation, convergence, and binocular disparity depth cues

nVidia . Santa Clara

Light Field Near to Eye Display







Innovega Corp., WA.

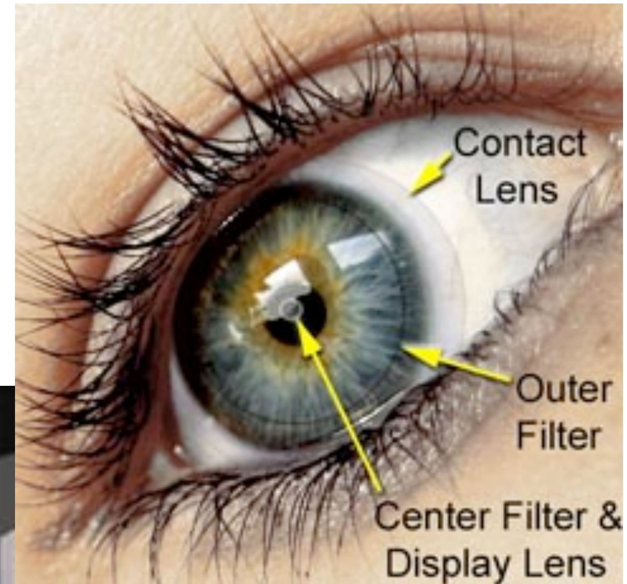
2 product architectures each using a combo contact lens + glasses hardware

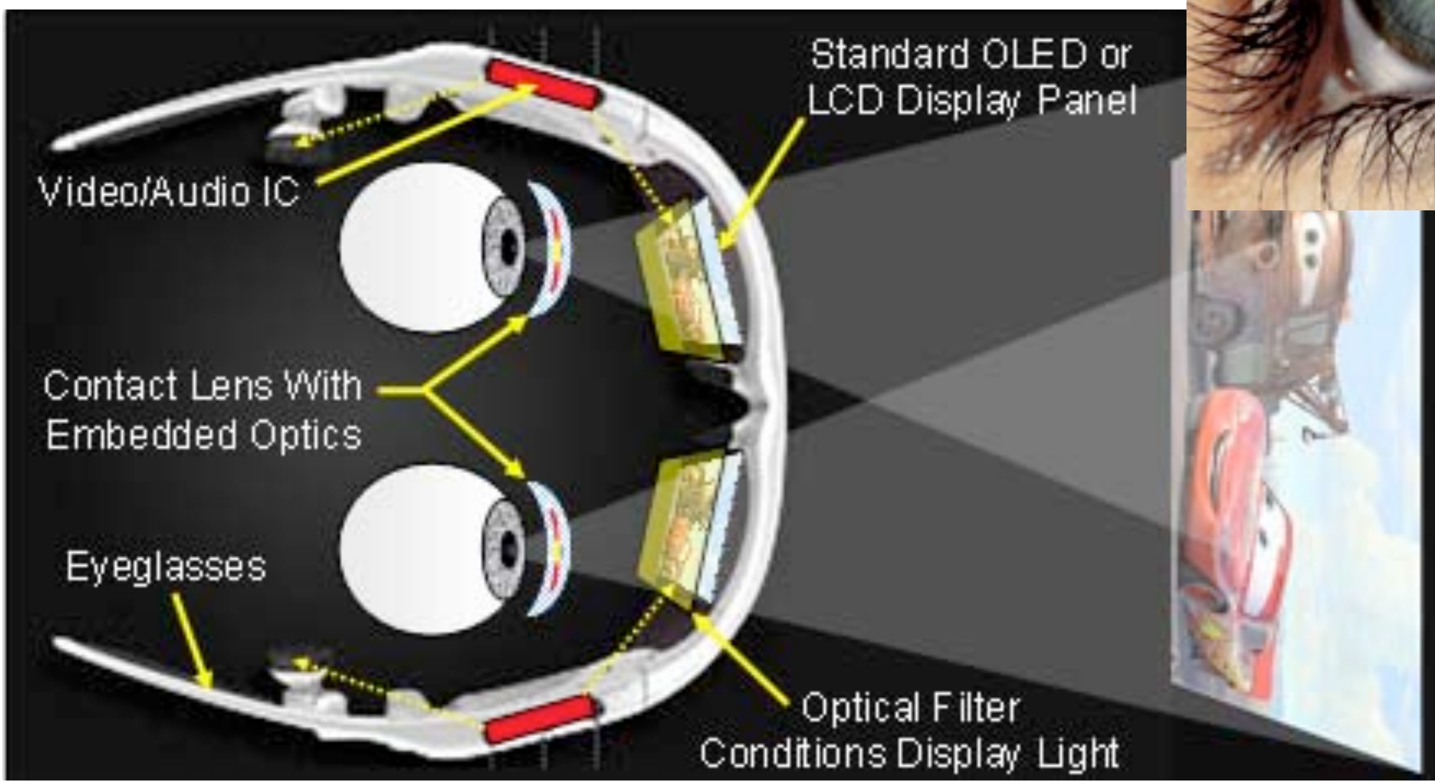
- First uses contact lens (with microlens) to collimate OLED located on glasses (non see through)

-Second uses contact lens (with microlens) to collimate image formed by laser scanner picos located on temple side, image is retro-diffused by reflective hologram located on inner surface of glasses (hologram creates retrodiffusion in ON-Bragg and see through in OFF-Bragg)

Complex R&D effort with DARPA financing using US and Swiss University, initiated by Microvision execs

Innovega Corp., WA.
2 product architectures each using a combo contact lens + glasses hardware





Google

The holly grail of Smart Glasses: Rx glass integration « make technology disappear »

Combo Rx lens + optical combiner: a challenge

If display and optical combiner are located AFTER prescription lenses, vision correction is effective for both digital and real scenes, and requires only generic combiner optics

Although optimum on a vision correction point of view and practical when updating Rx prescription, this is not ideal since:

1) dual optics in front of eye

2) increases eye relief thus reduces eye box

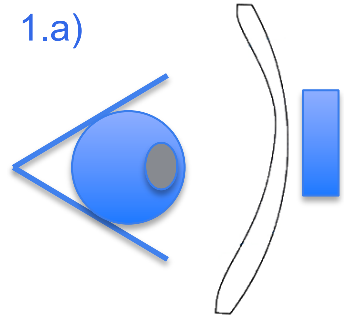
3) technology not disappearing

Potential combo Rx / Combiner architectures

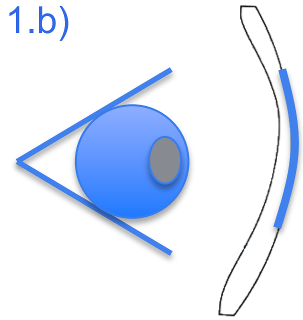
1) Rx lens UNDER combiner
   a) combiner independent of Rx lens
   b) combiner shares outer shape of Rx lens

Generic uncompensated combiner

1.a)



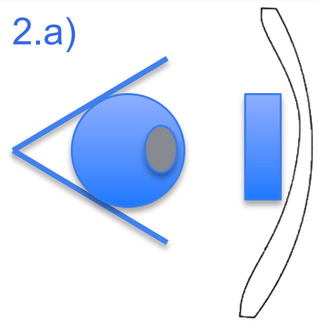
1.b)



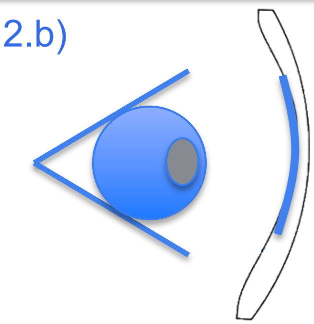
2) Rx lens OVER combiner
   a) combiner independent of Rx lens
   b) combiner shares inner shape of Rx lens

Combiner to be compensated for Rx

2.a)



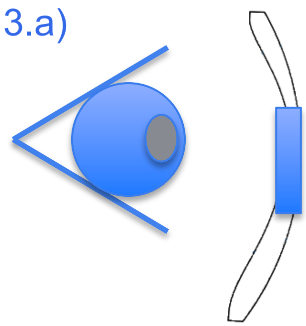
2.b)



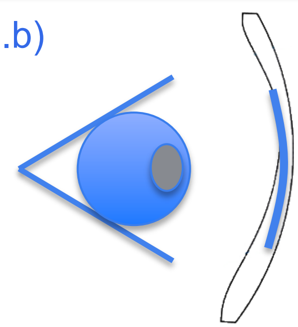
3) Combiner INSIDE Rx lens
   a) flat or curved combiner requiring TIR and injection port
   b) flat or curved combiner not requiring TIR and injection port

Compensated combiner optics

3.a)



3.b)



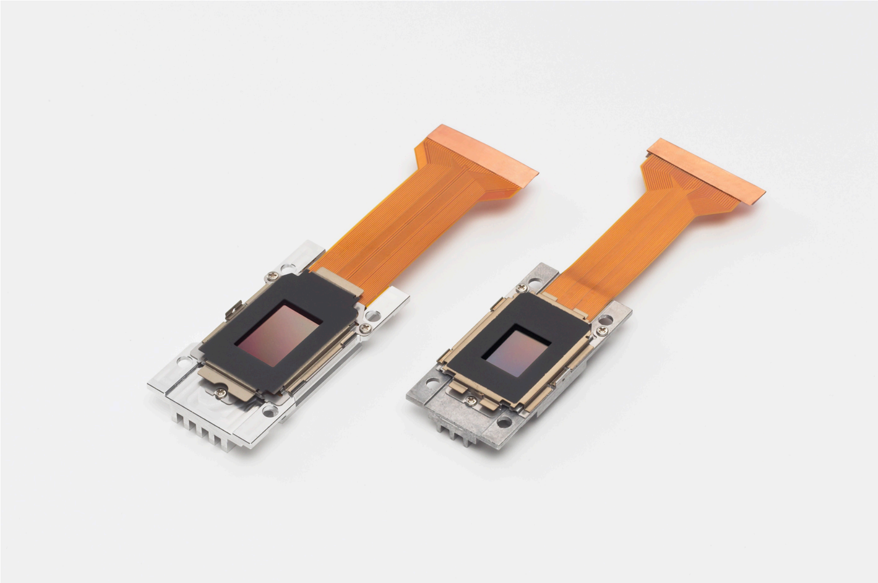
Rx integration example from Essilor

Purpose: Correcting Age-related Macular Degeneration (AMD)

Essilor AMD product: Camera is on right side (user side), and display is on left side.

Microdisplays technologies for wearable displays

Reflective LCOS type

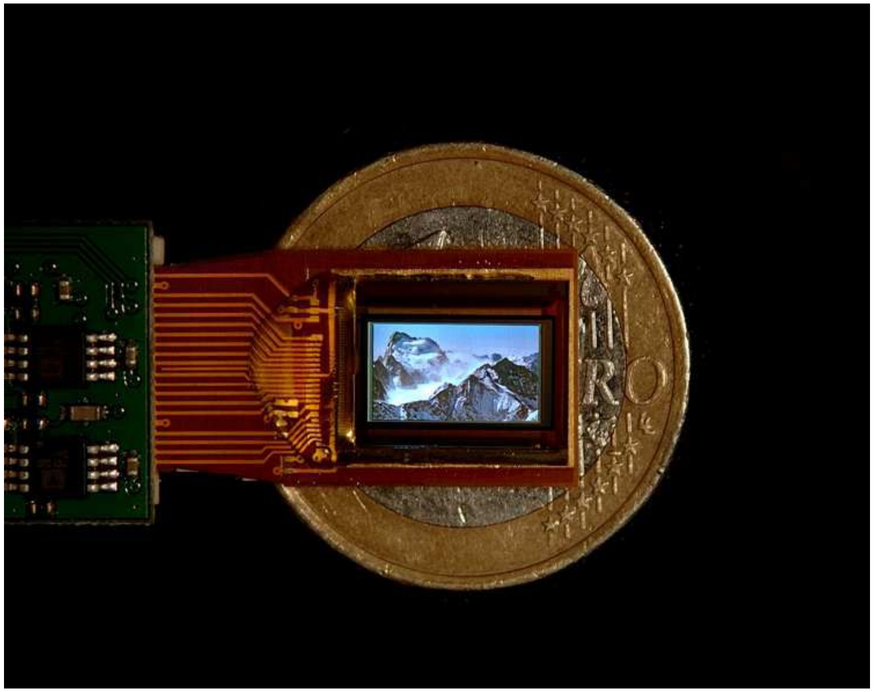


Requires either glass PBS cube or front light edge lit assembly.
Low efficiency.
Polarized light field.

Transmissive LCD type

Low efficiency, requires LED edge lit backlight or conventional LED collimator. High efficiency when using single color LED without color filter. Polarized light field.

OLED type



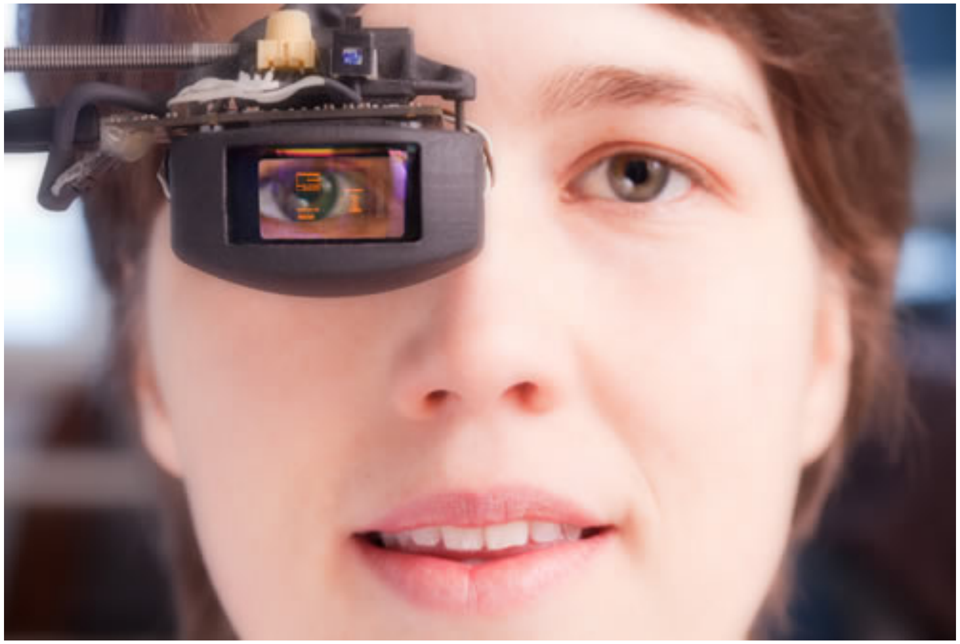
Emissive display, higher efficiency than LCOS or LCD, but Lambertian emission.
Silicon backplane, pixels down to 4 microns.
Current development aims at getting rid of color filters (direct color OLED patterning).
Unpolarized light field.

MEMS laser scanners

Single or dual MEMS mirrors
Low power consumption
Adaptable FOV – far field image projectors
Laser light, despeckeling required.

Google

Fraunhoffer's combiner based on bidirectional OLED



Interesting for HMD eye gesture sensing in the display plane

Google

Another challenge REMAINS for next generation smart glasses : The interation mechanism

Another challenge remains: The data entry interface.

HMD industry already has integrated:

Another challenge remains: The data entry interface.

HMD industry already has integrated:

- Voice command

Another challenge remains: The data entry interface.

HMD industry already has integrated:

- Voice command
- Head motion tracking (magnetometer, gyro, accelerometer)

Google

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- Gaze tracking, eye gesture sensing, wink sensor, etc…

Another challenge remains: The data entry interface.

HMD industry already has integrated:

- Voice command
- Head motion tracking (magnetometer, gyro, accelerometer)
- Trackpad interface
- Gaze tracking, eye gesture sensing, wink sensor, etc…
- Gesture sensing through front facing camera and structured illumination

Google

Recent happy marriages in this field

Microsoft  CANESTA™

Microsoft®

CANESTA™

PrimeSense

Microsoft

CANESTA™

PrimeSense

intel

TYZX | systems that see

Microsoft

CANESTA™

PrimeSense

intel

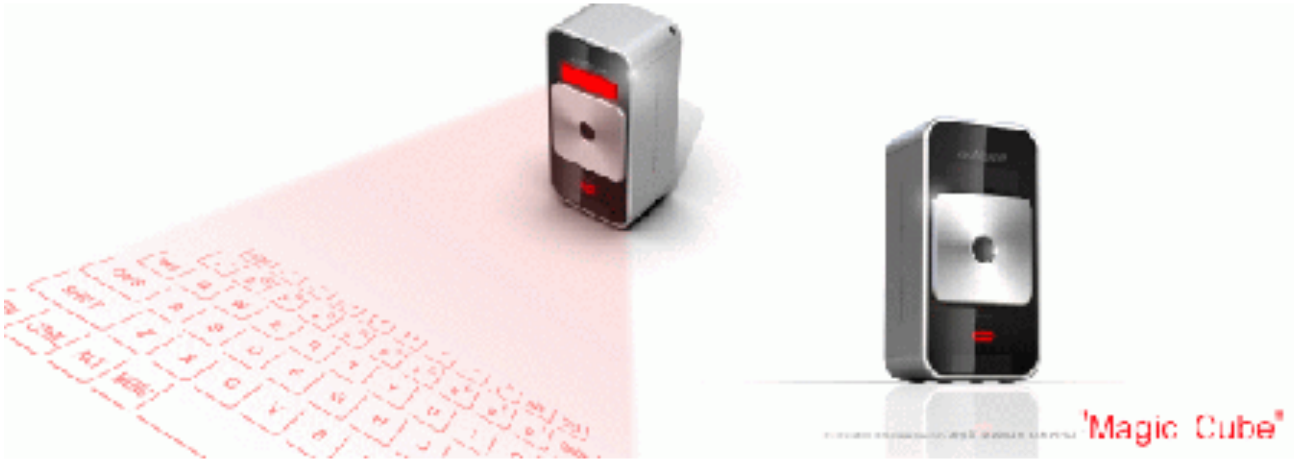
TYZX | systems that see

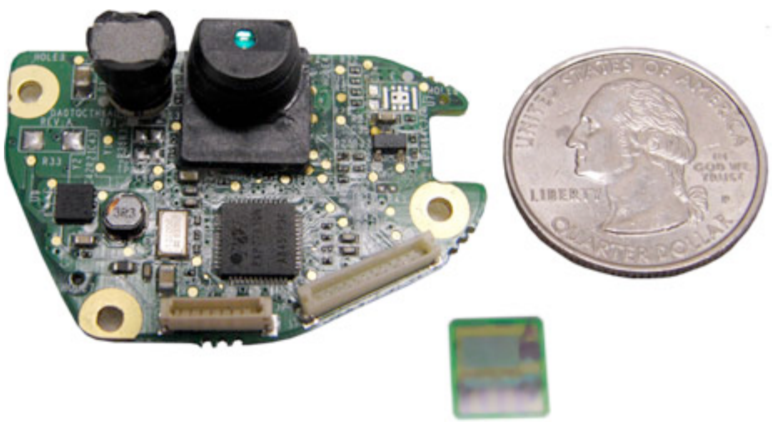
Google™

Examples of gesture sensing using structured illumination and/or time of flight

Canesta develops structured illumination for virtual interfaces and uses Time Of Flight to sense finger positions

(however, it was IBM who invented the virtual keyboard in the first place).

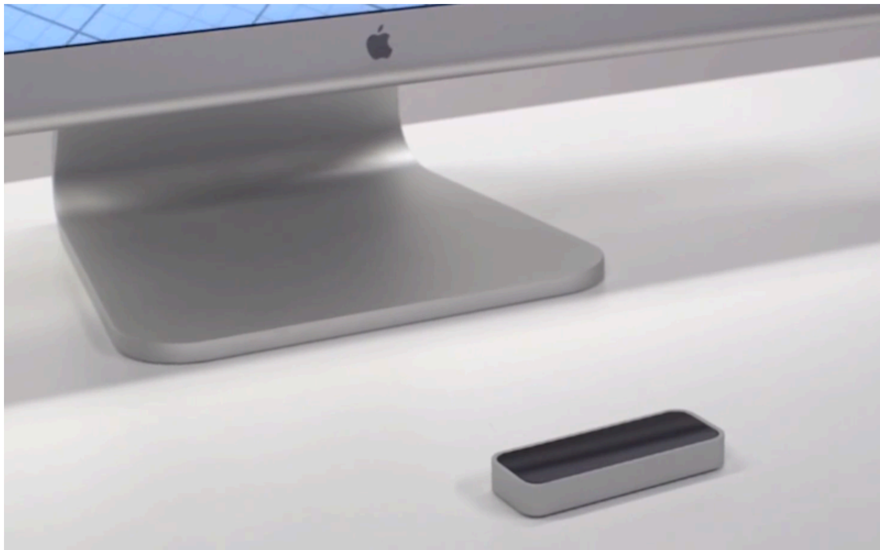


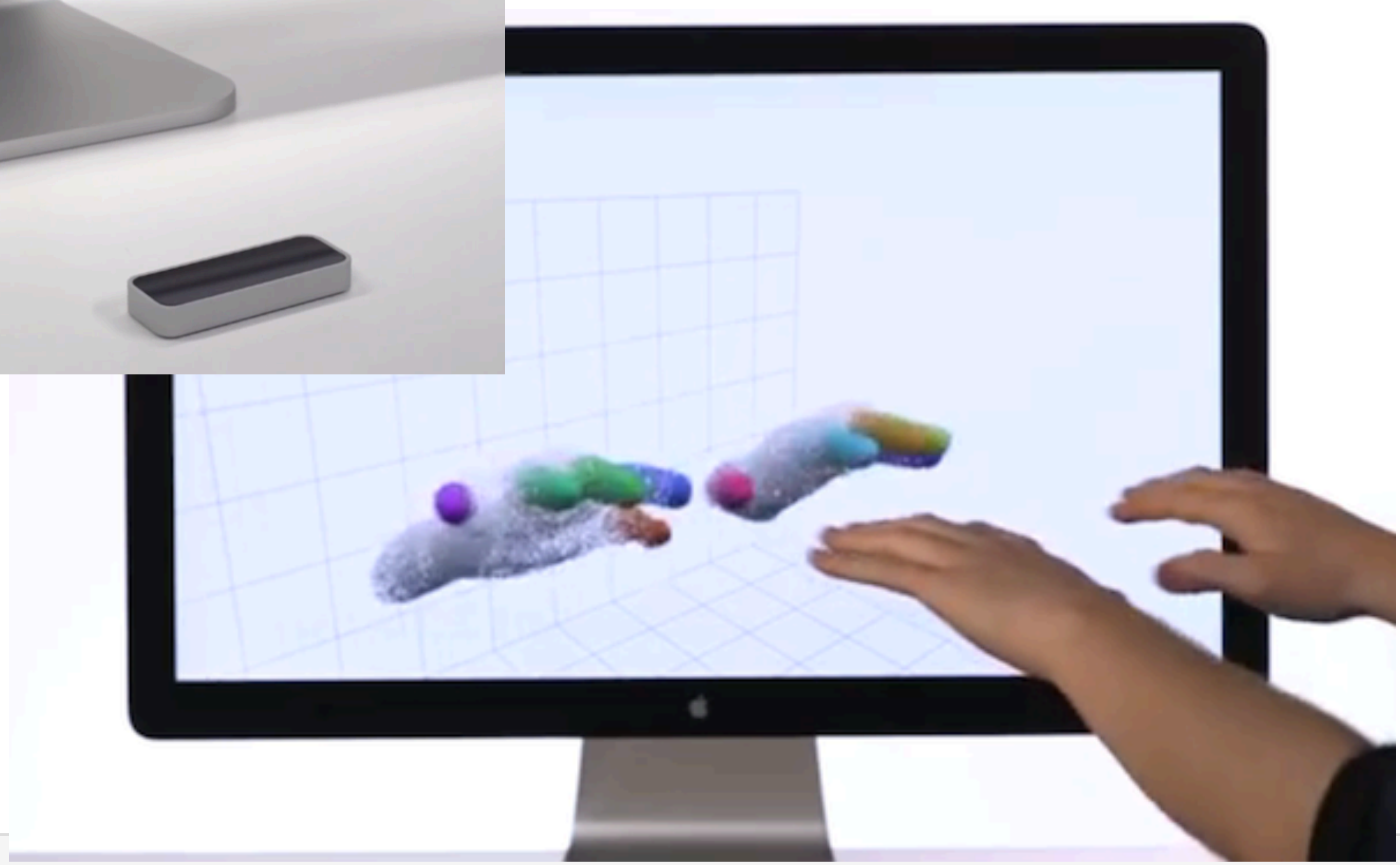


Celluon develops similar technology based on Canesta IP.

Light Blue Optics device incorporates a holographic LCOS diffractive projector for virtual interfaces, and a camera for gesture sensing.

Leap Motion does not use structured light, instead uses flood IR illumination and uses two cameras to acquire shadows.



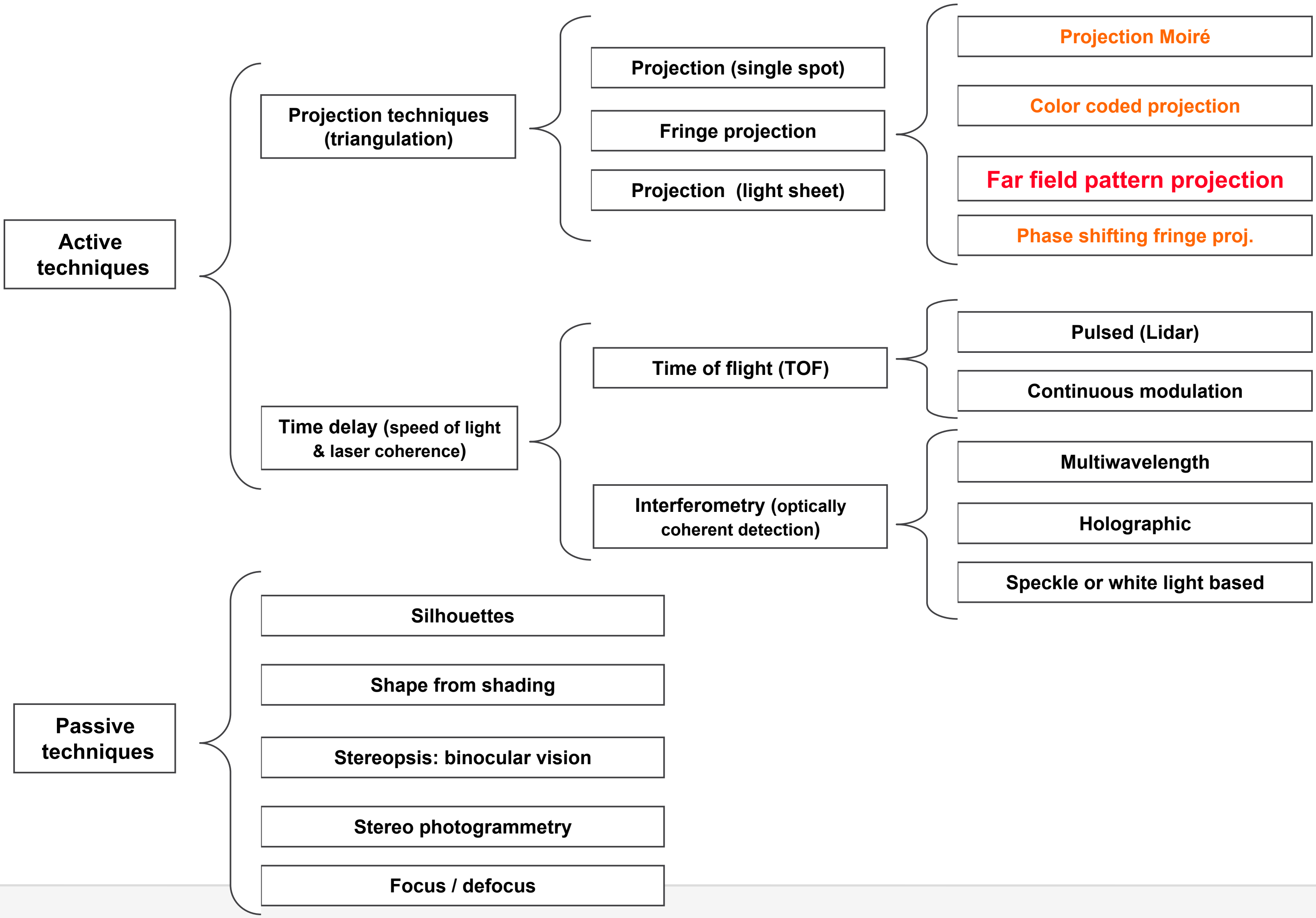


So, how to integrate such technologies in head mounted displays…

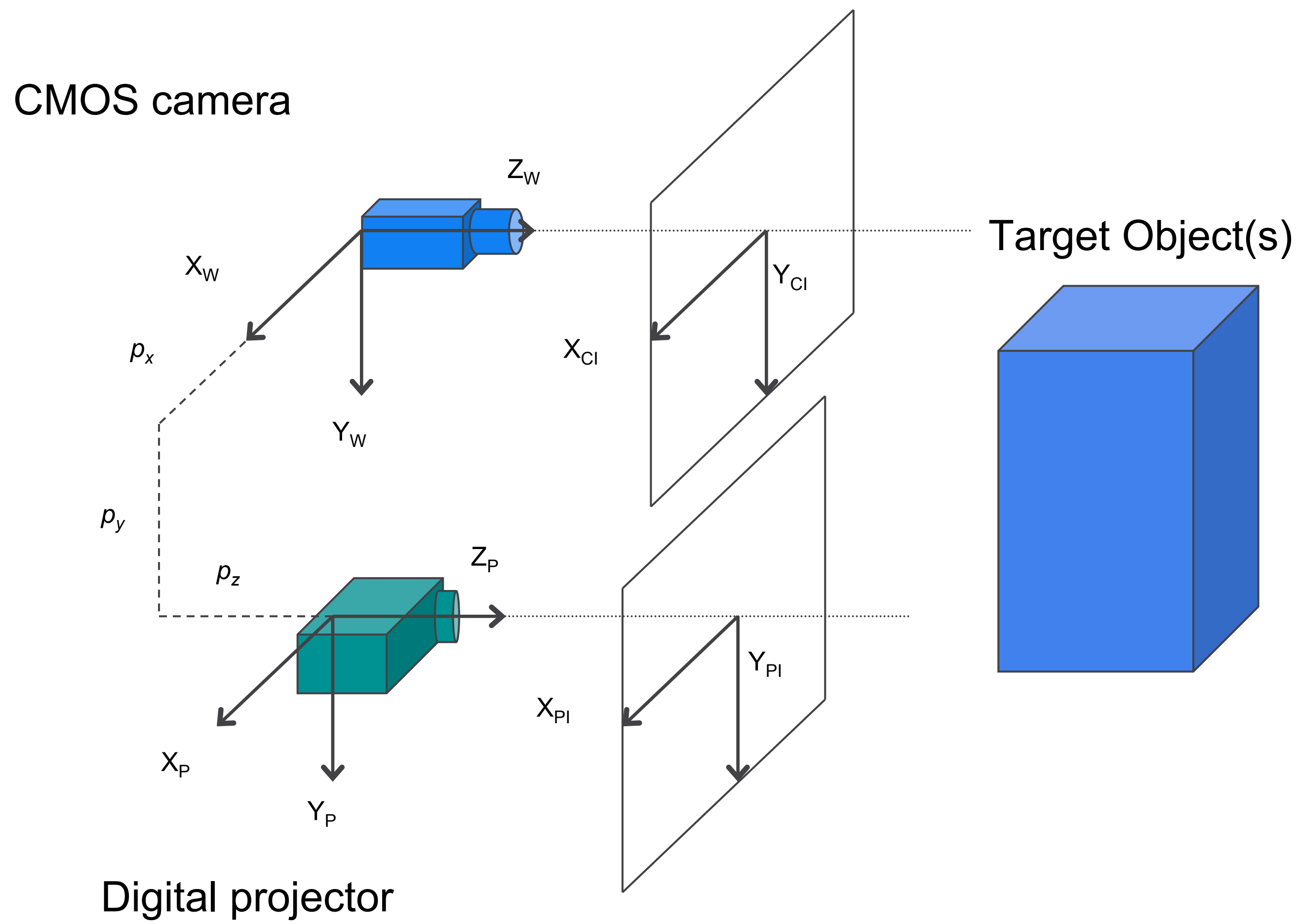
… to look less like this…

… and a little more like this

Today's 3D optical sensing available arsenal

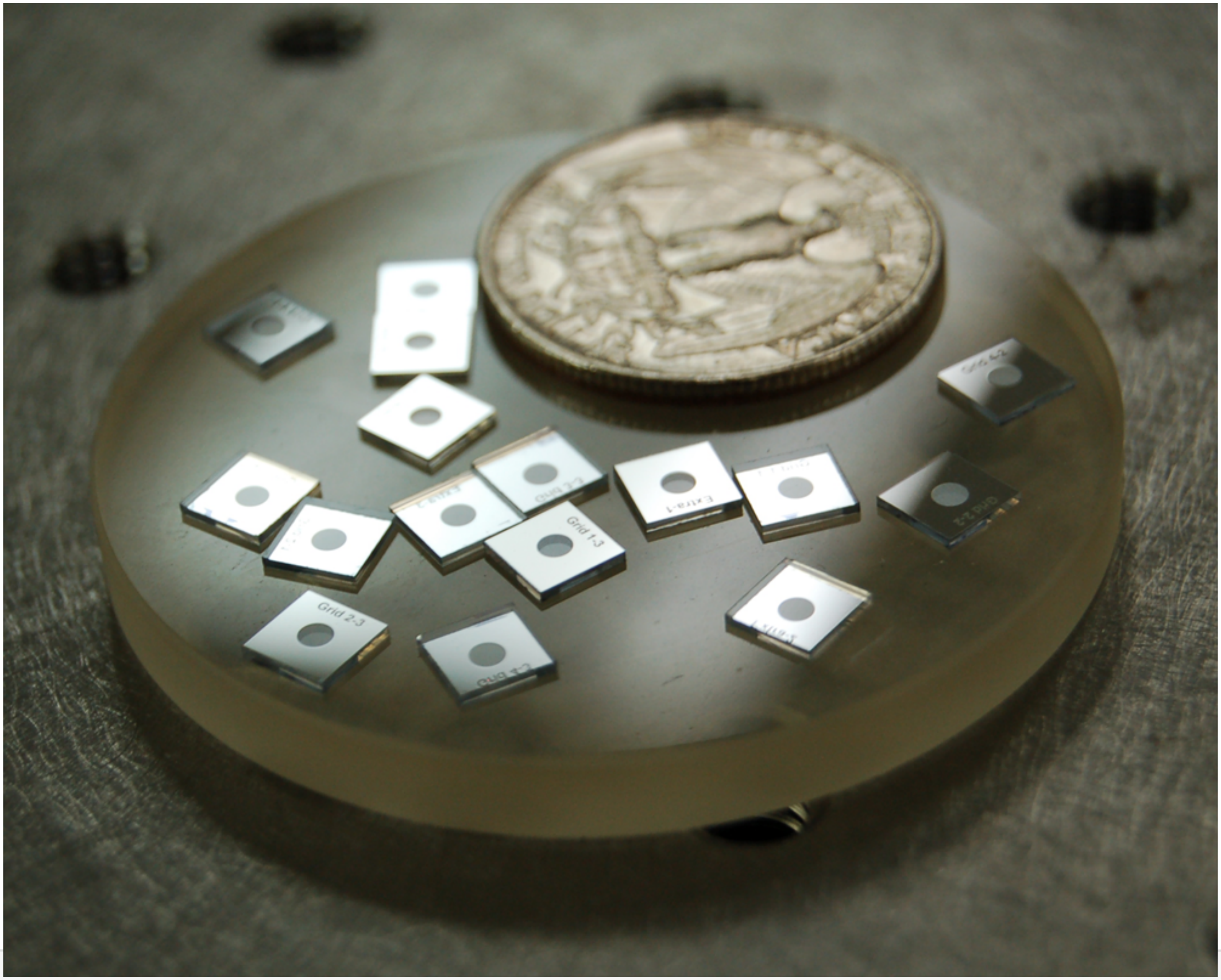


Principle of structured illumination for 3D maping

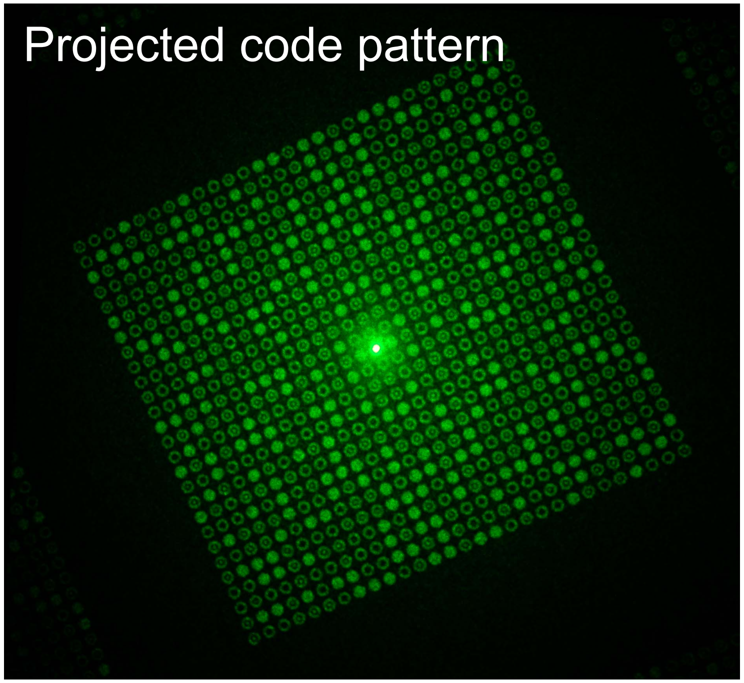


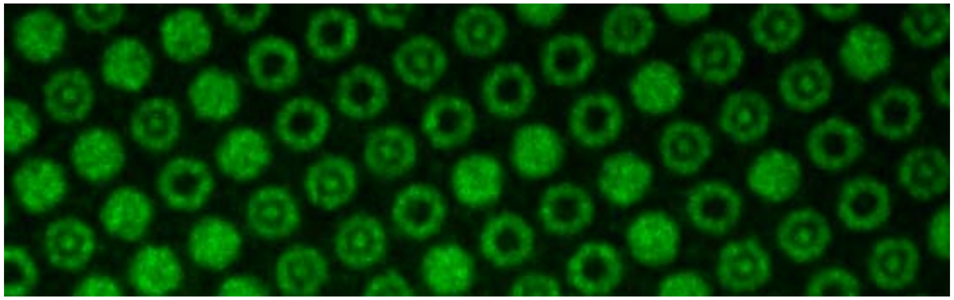
Traditional weaponery used for 3D scanning via structured illumination using multiple fringe projection

Diffractive projectors are small and cheap

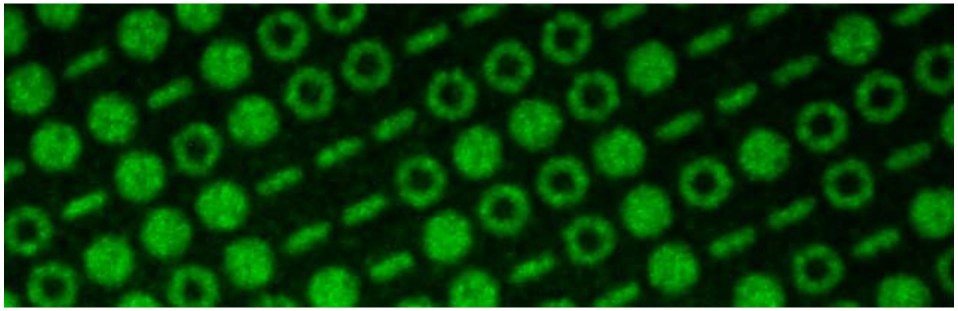


… with more complex structured illumination…

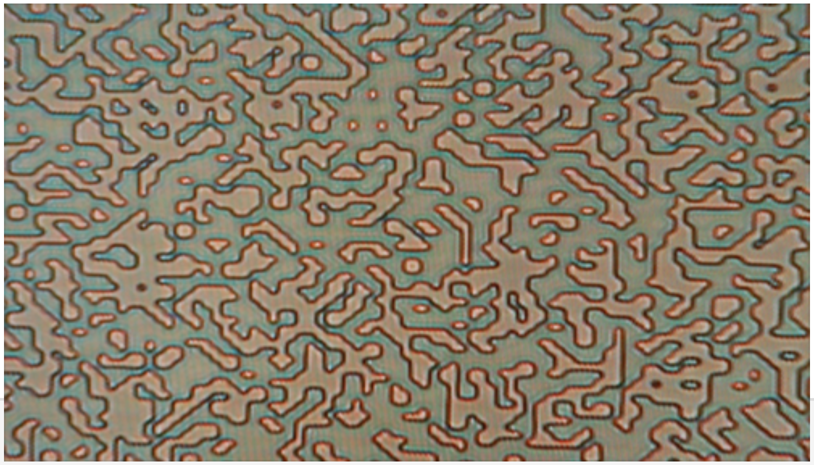




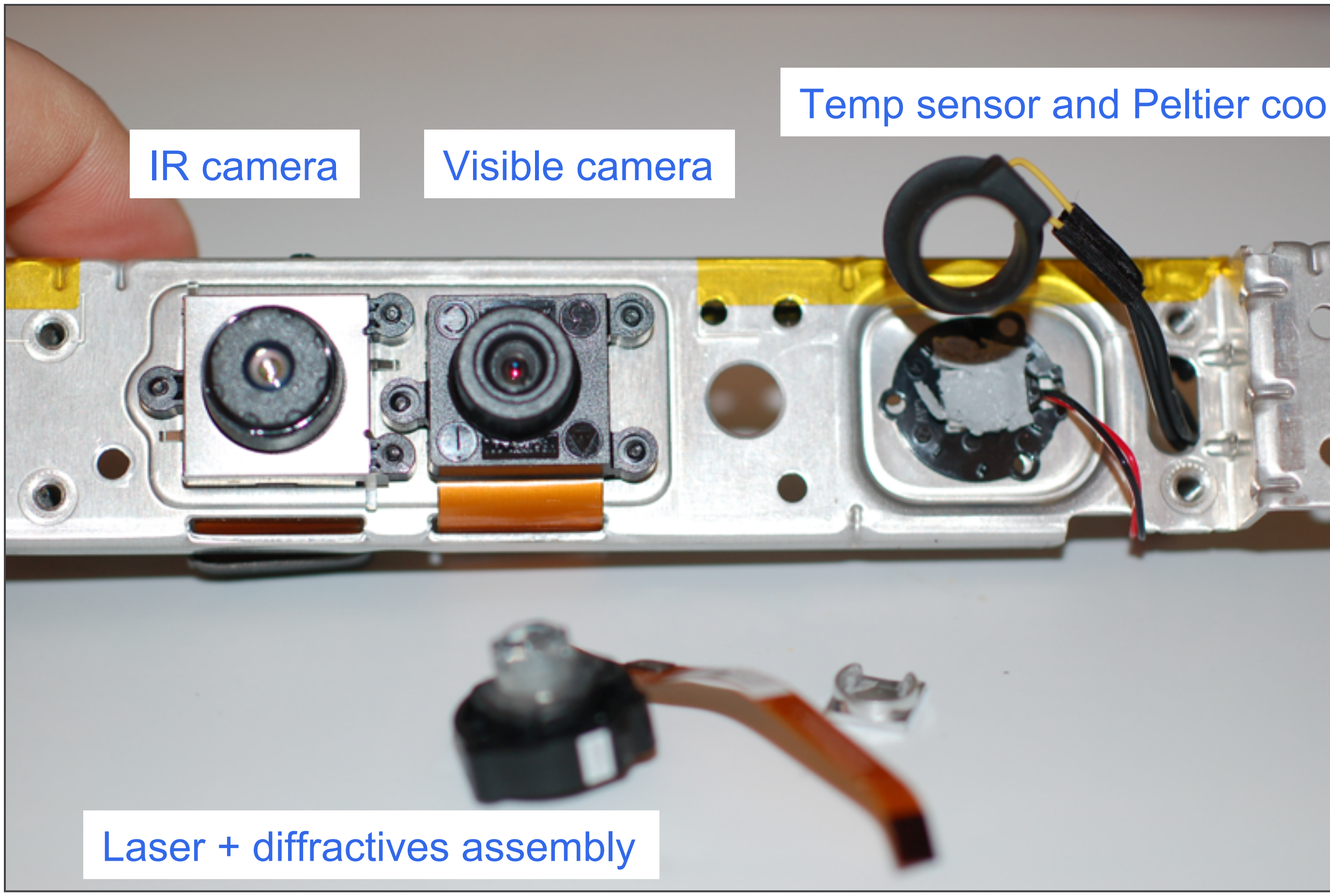
Zoom on patterns / non-repeating 3x3 codes



CGH structures as under microscope



Primesense KINECT: Two cameras (visible and IR) and a diffractive projector

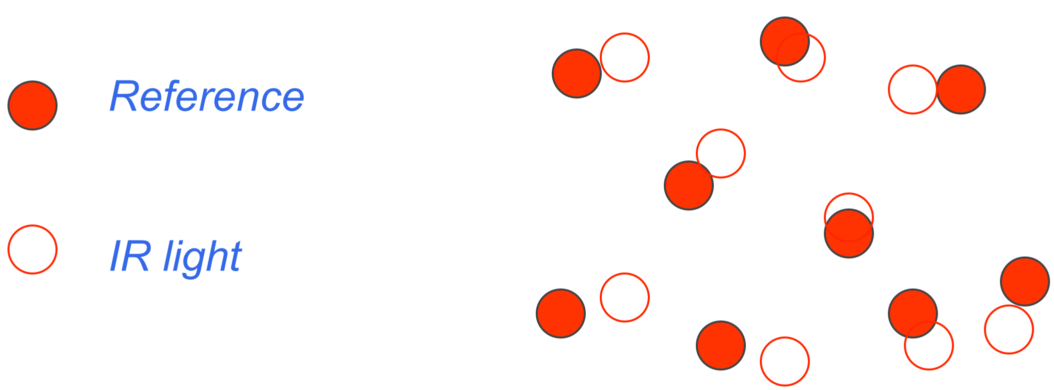


How does it work?

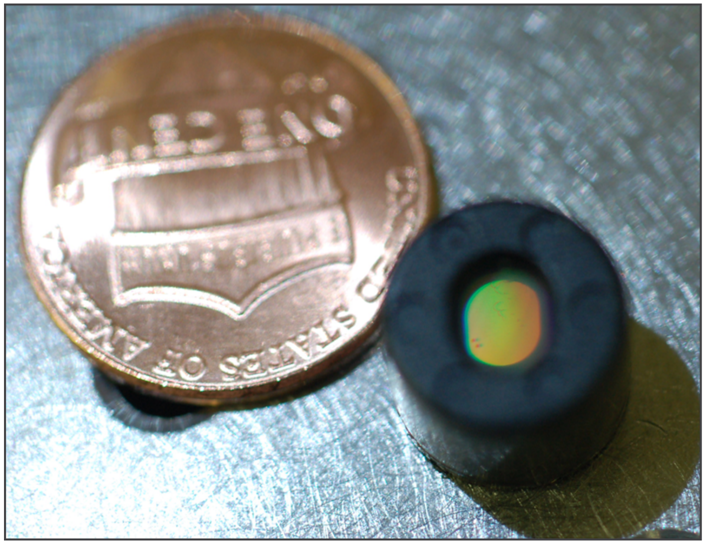
Kinect uses pixel offsets from a calibrated reference image (stored in memory) to transfrom an infrared image (@820nm) of the structured light pattern into a depth map.
Kinect can compute pixel offsets to 1/8 subpixel accuracy using a 9x9 pixel correlation window on a 2x2 downsampled image from the infrared camera.
The associated relationship between depth and pixel offset is given by:

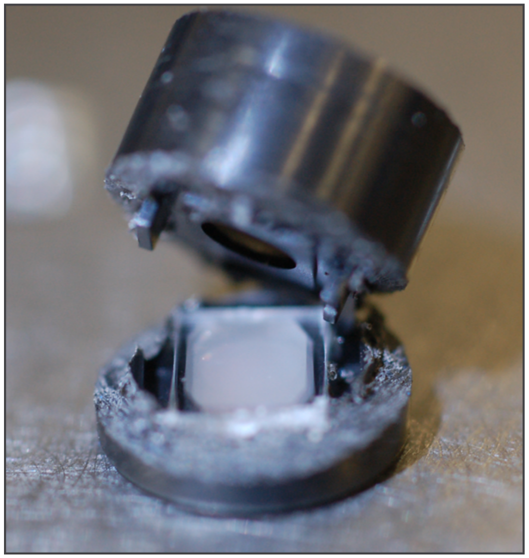
$$z = \frac{8bf}{disparity\,offset - Kinect[pixel]\,disparity}$$

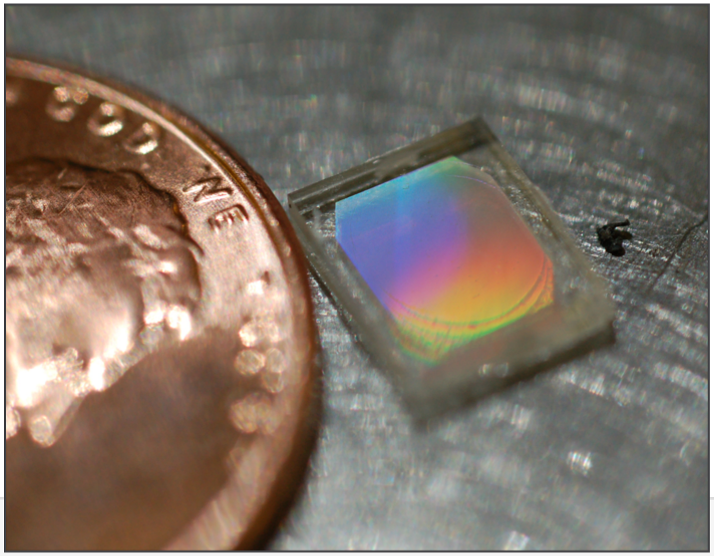
… where b is the camera-projector baseline separation and f the infrared camera's focal length.



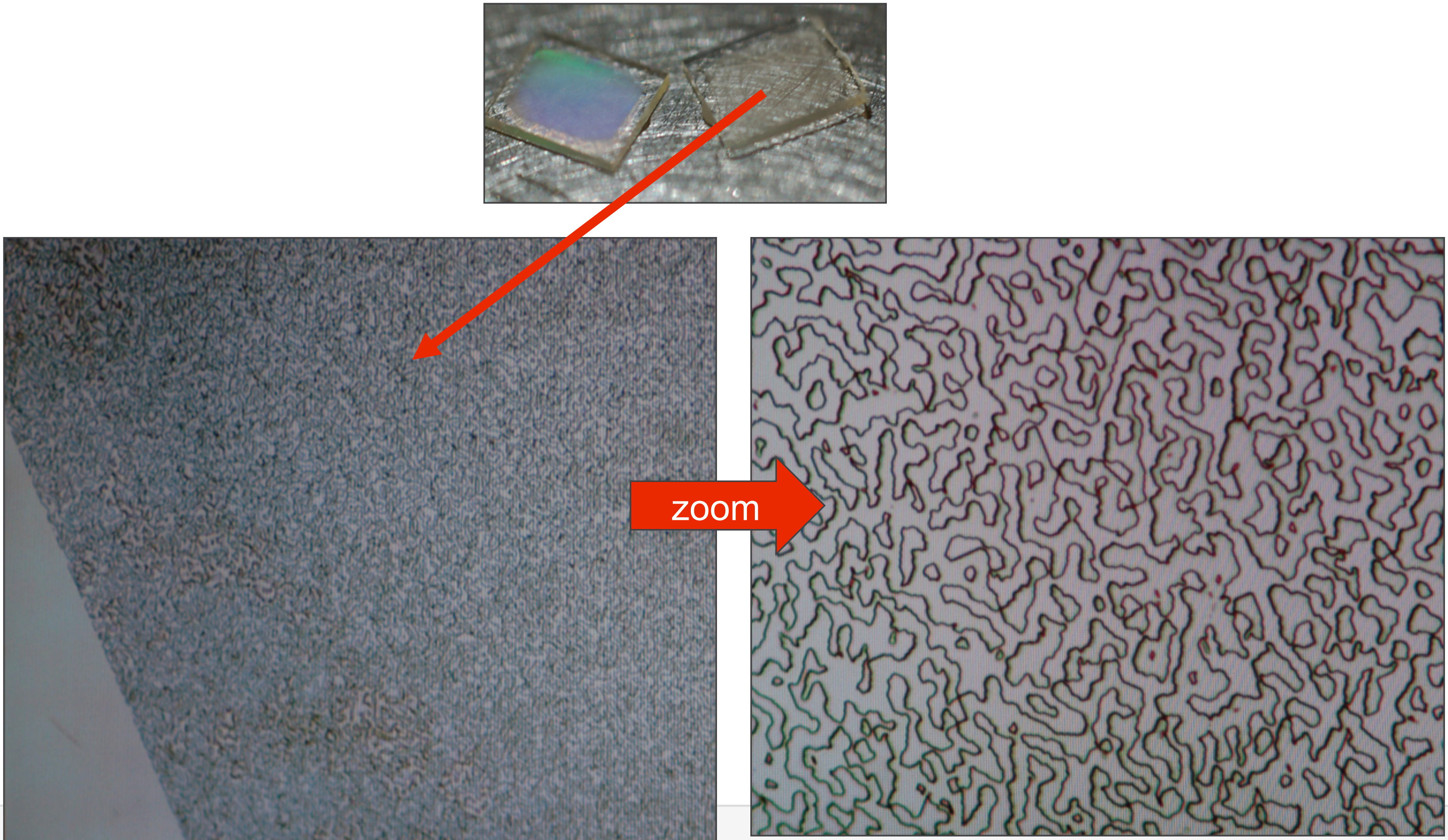
Dual diffractives package assembly
-> producing optical convolution between a CGH and a crossed grating



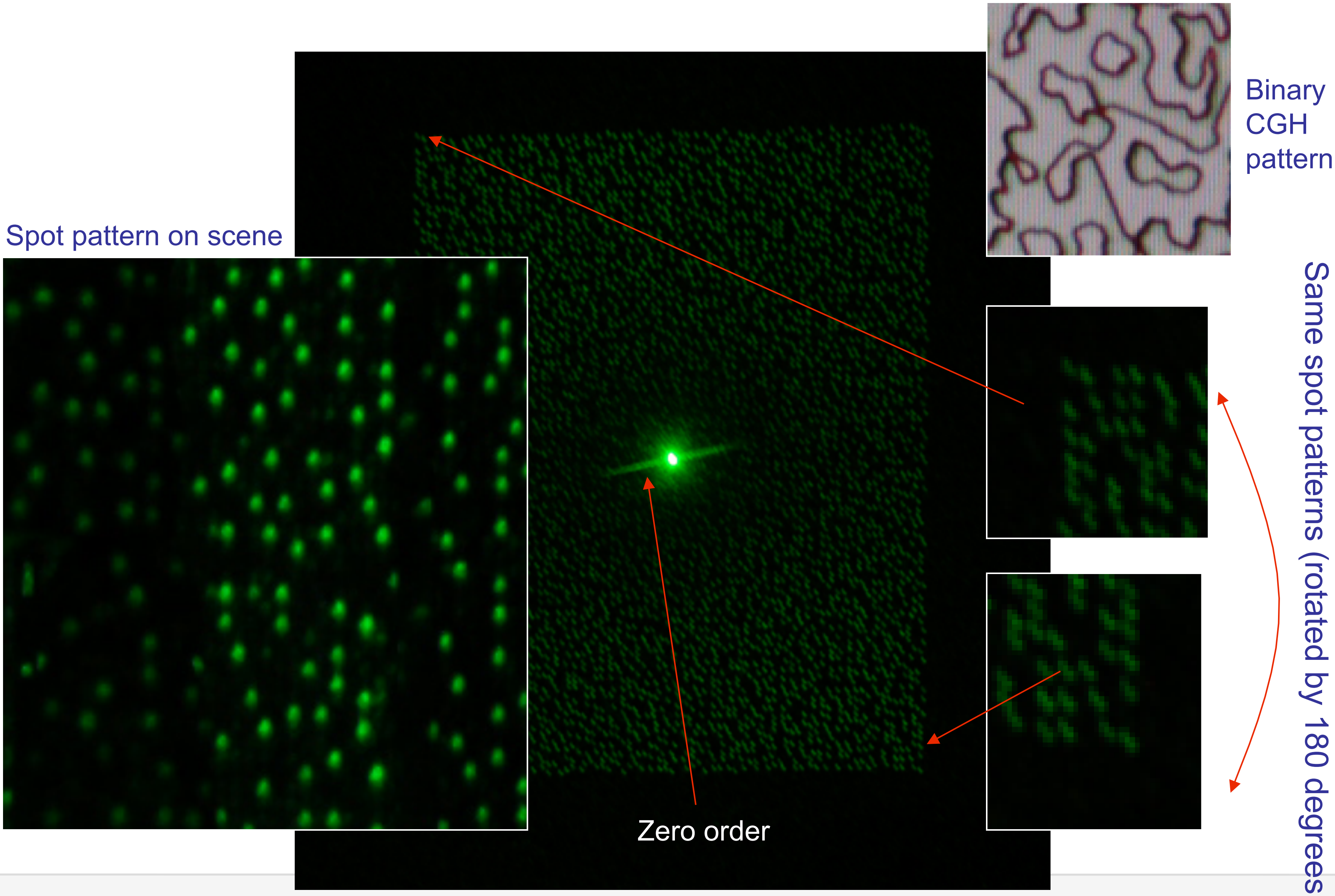




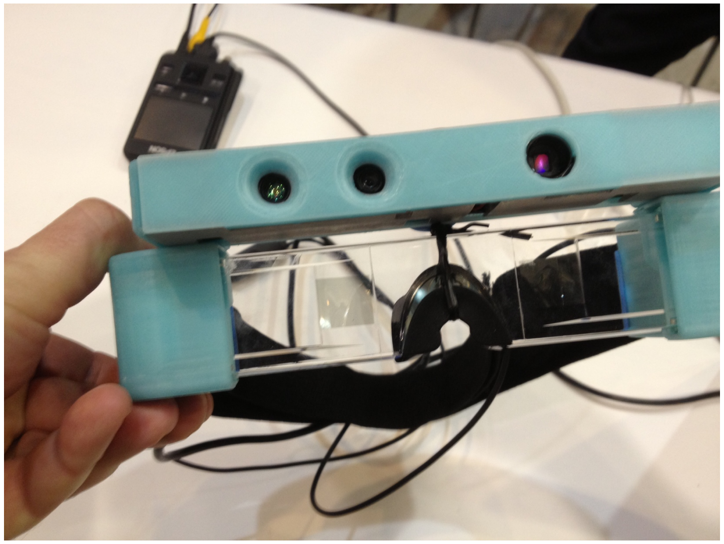
Pattern generator CGH microscope pictures.



Single tile pattern projection from CGH element

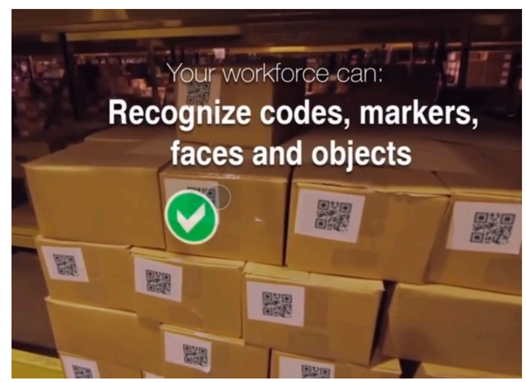


Two examples of Epson Moverio binocular see through displays linked to Kinect Primsense gesture sensor (presented at AWE 2013)

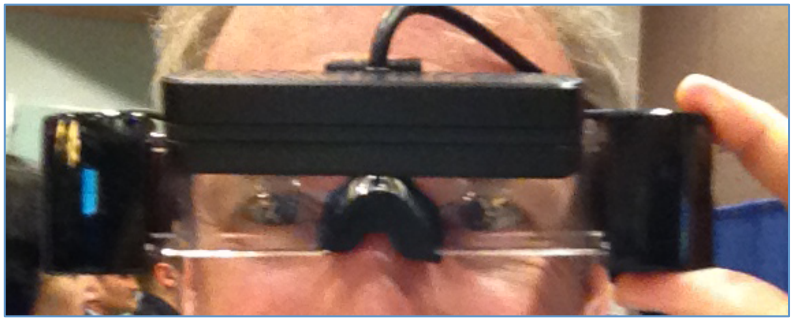


Scope Assist. APX Skylight and Evena

Use Epson Moverio hardware for engineering and medical professional applications



META Glasses (Space Glasses)
Integration of Epson Moverio HMD (1st and 2nd gen)
with Kinect gesture sensor (1st and 2nd gen also)
Not a hardware company, but rather AR software



Today

META Glasses (Space Glasses)
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Today

Tomorrow

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Today

Tomorrow

Day after tomorrow

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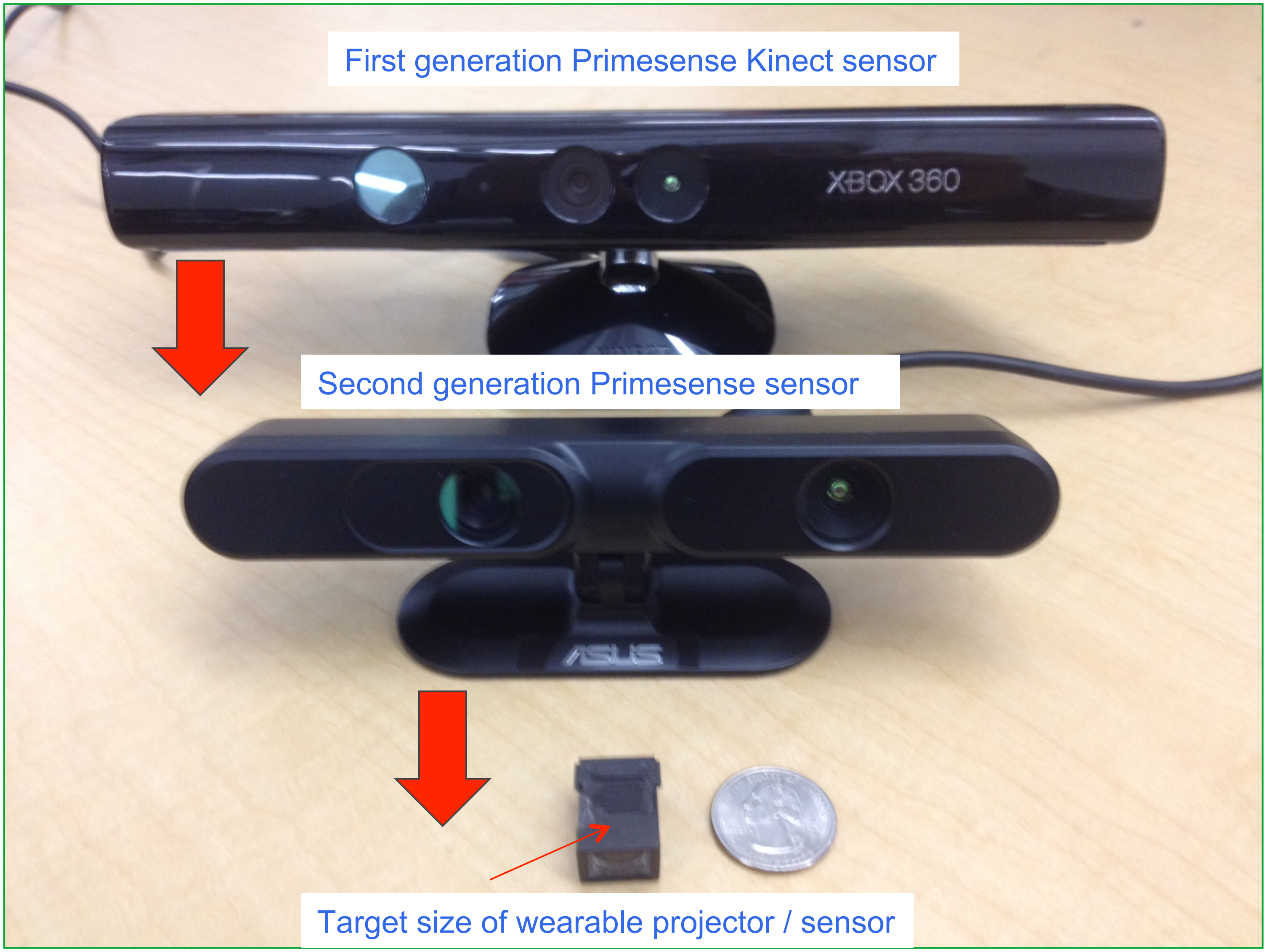
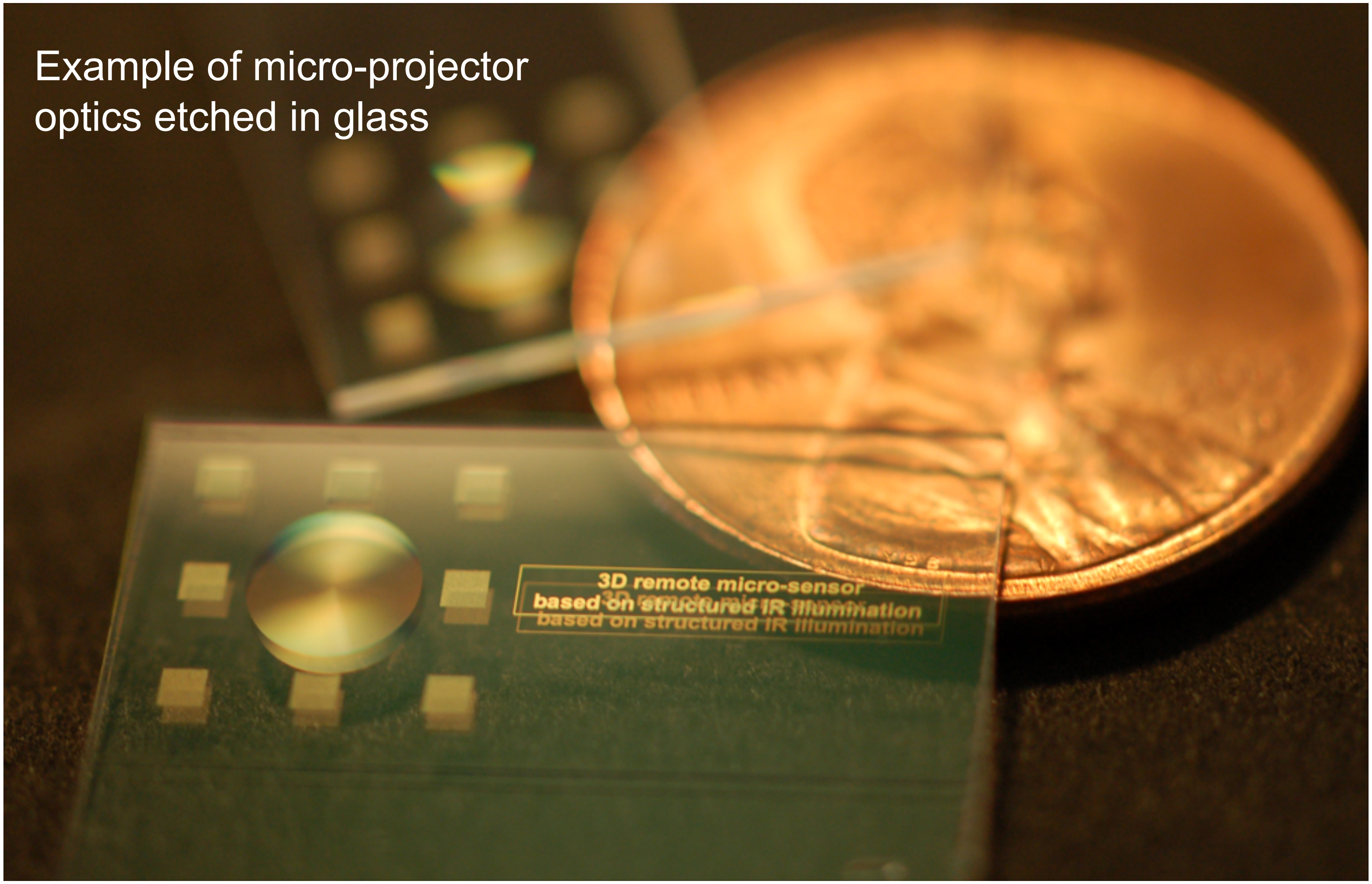

First generation Primesense Kinect sensor
XBOX 360
Second generation Primesense sensor
/ISUS
Target size of wearable projector / sensor

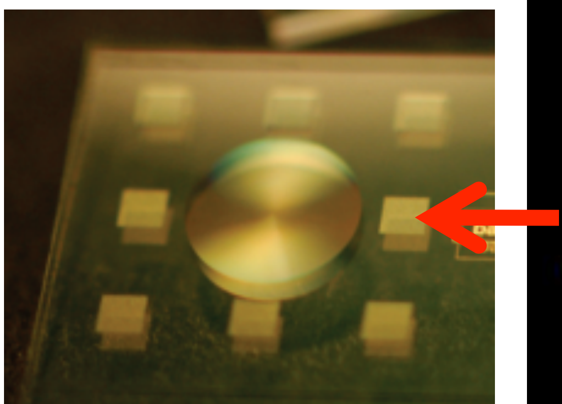
How small can one make the projector elements?

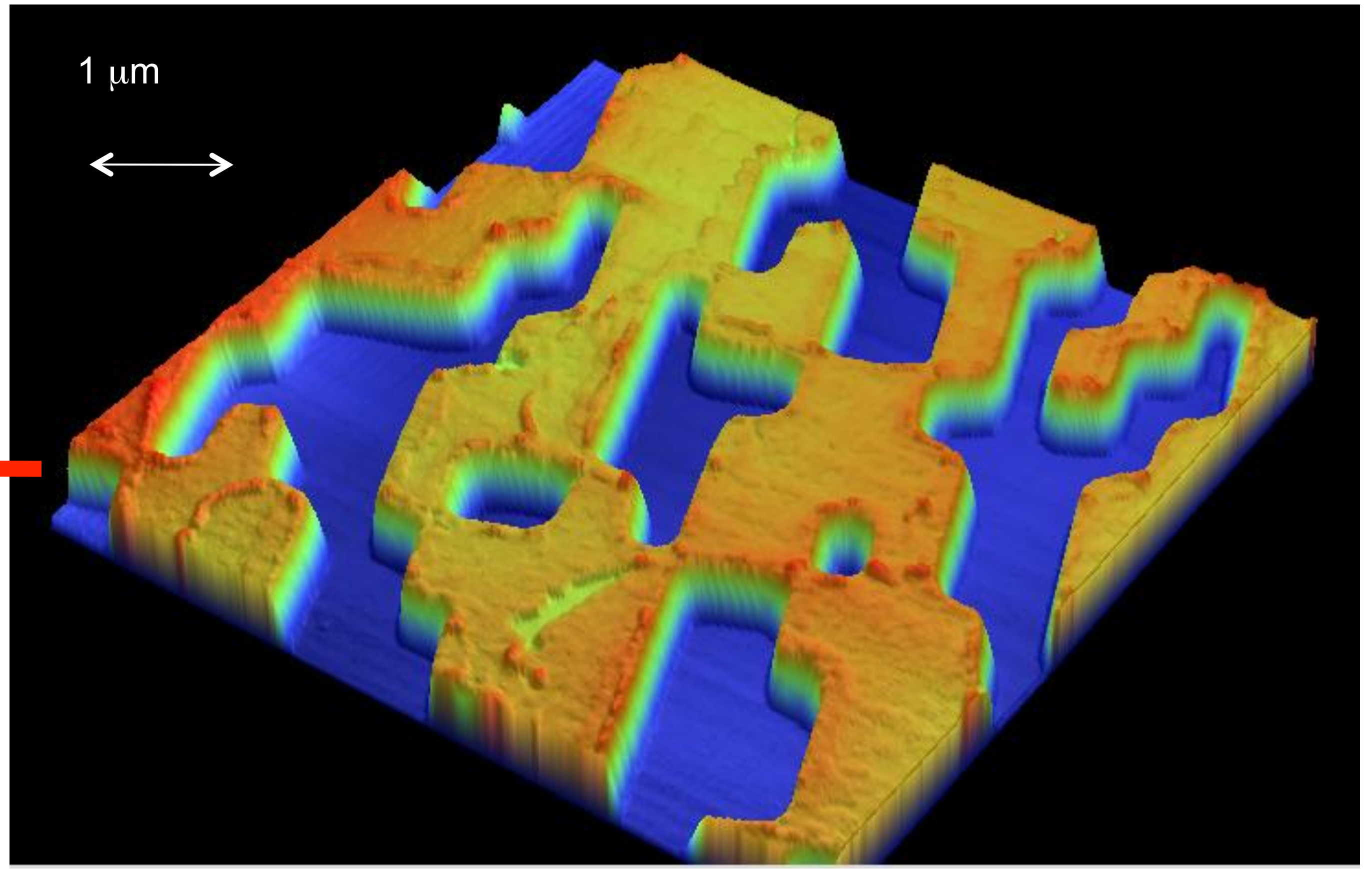


Example of micro-projector optics etched in glass

On this 3x3mm quartz window there are 8 different structured light projectors (for sensing and virtual interfaces), as well as an EDOF IR camera objective lens.

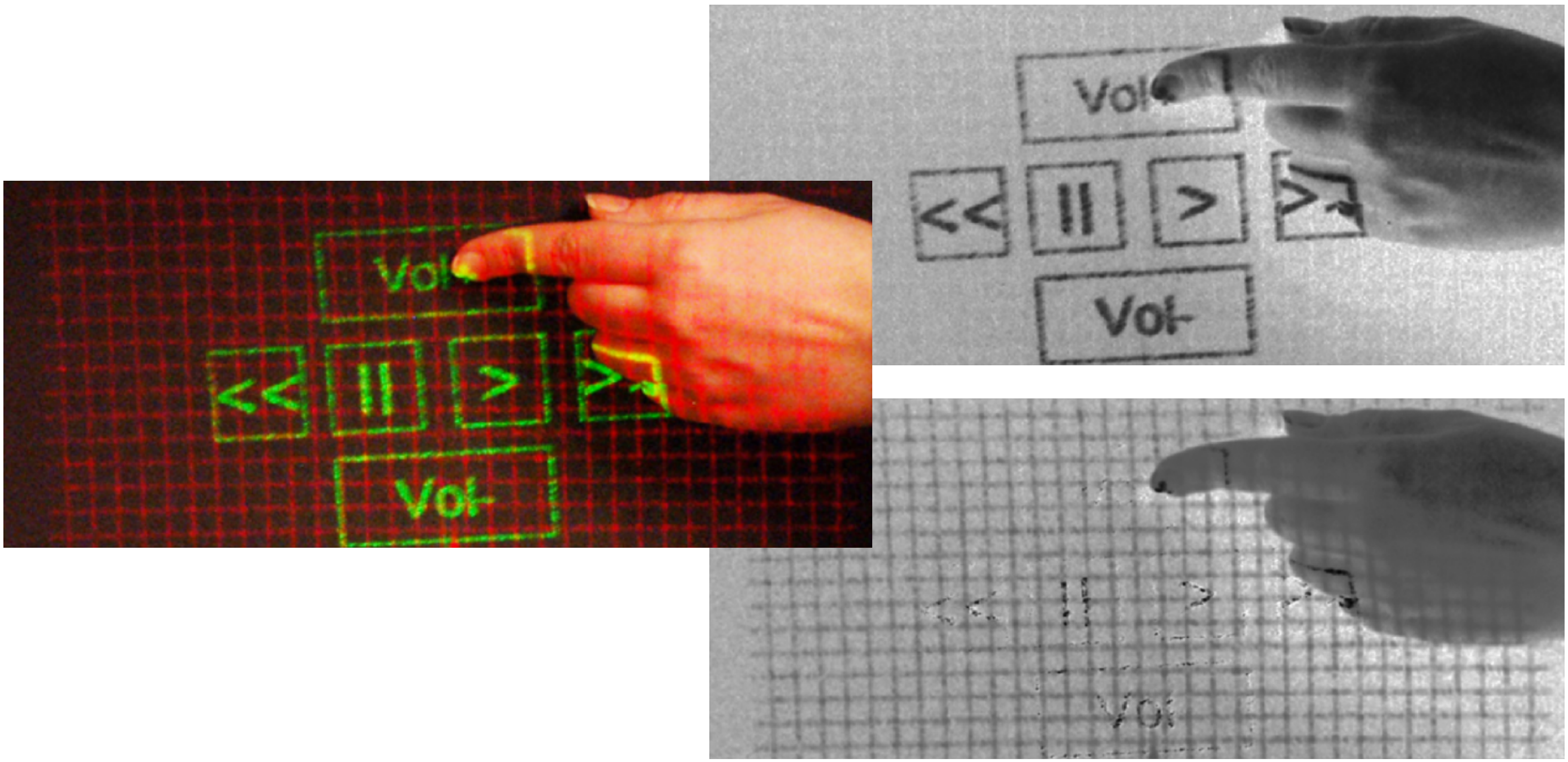
Surface topology scan over structured light pattern generator etched in quartz window





Example of virtual interface projection with simple structured illumination from previous piece of quartz.

RGB camera



IR camera

The key is to produce smarter optics and as a result reduce signal processing requirements
- smaller, faster, cooler, cheaper -

Google

The key is to produce smarter optics and as a result reduce signal processing requirements
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LeapMotion

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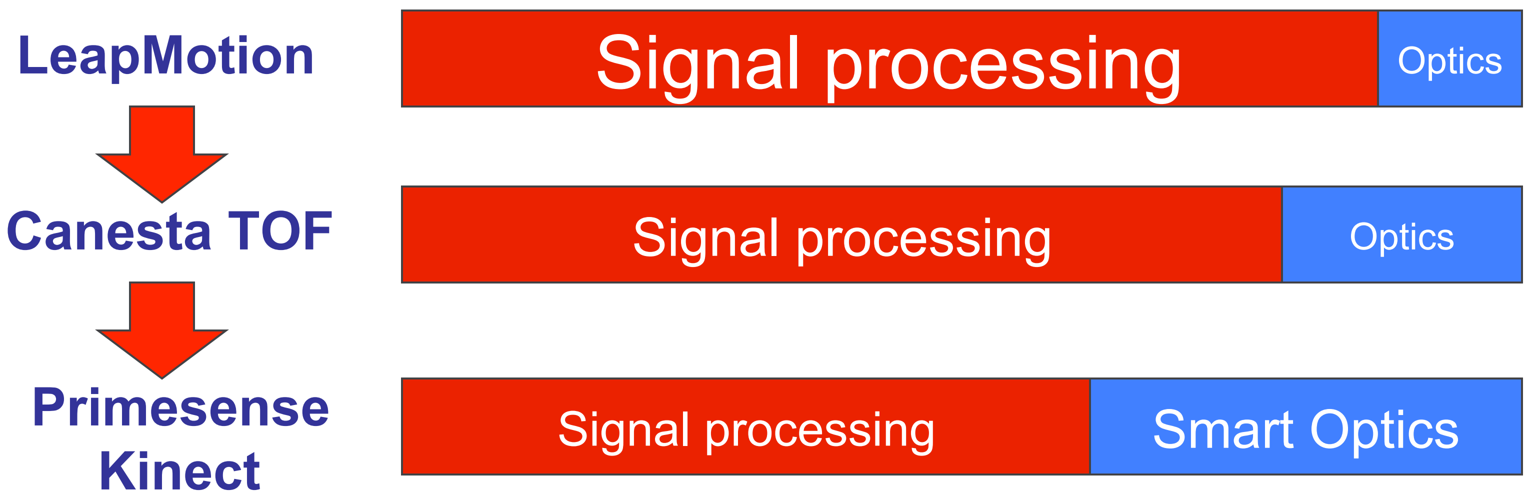

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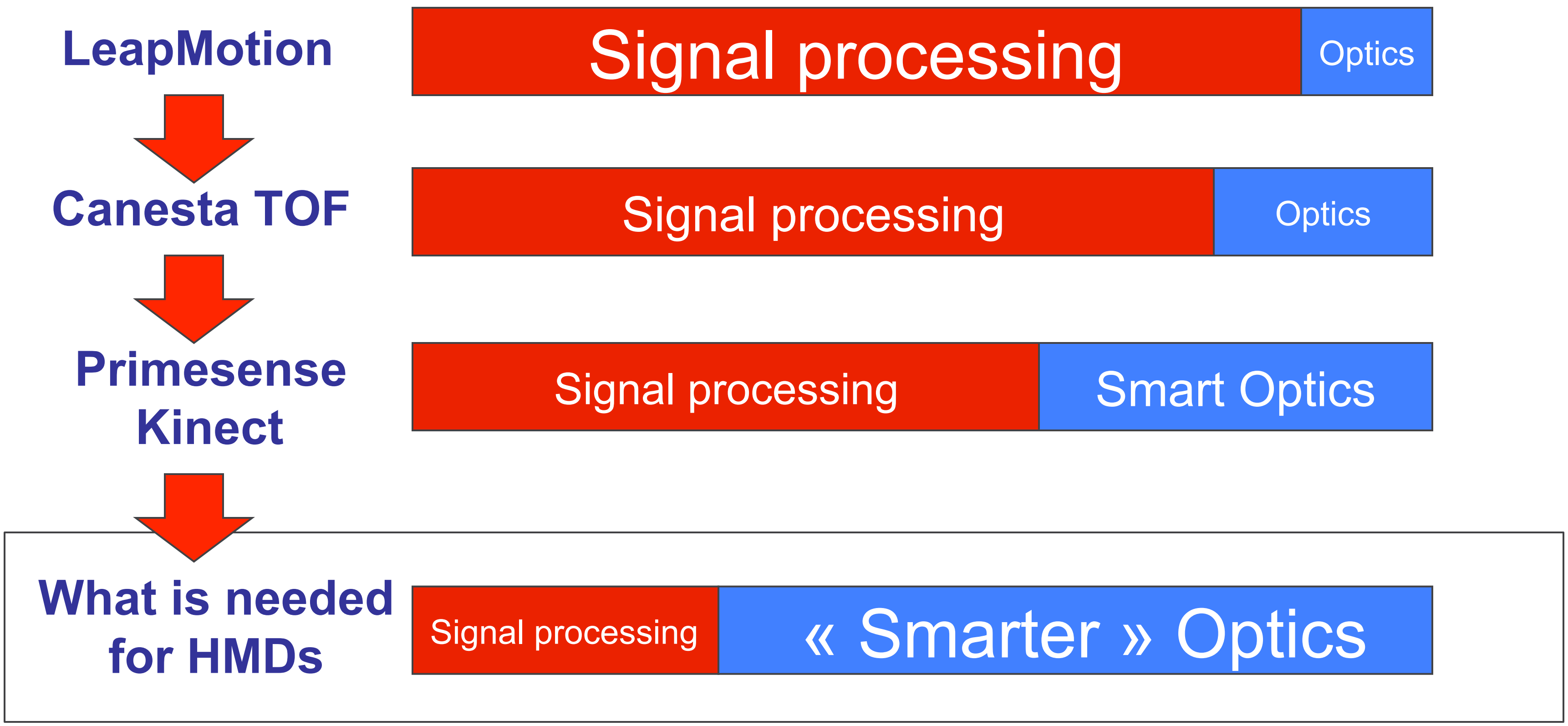

Conclusion.

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- Large eye box
- Optical combiner integrated within prescription lenses
- High resolution and large FOV over full color operation
- **… and seamless integration of virtual interfaces and gesture/eye sensing**

Google


THANK YOU
Grazie
Obrigado
Köszönöm
Mahalo
arigato
Спасибо
Takk
Рахмет
Gracias
Prasom
Danke
Dziekuje
Merci
Multumesc

Bernard Kress (bkress@google.com)