Freeform Optics for Optical Payloads with Reduced Size and Weight

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About Voxtel Companies

<u>VoxtelOpto 3D Imaging (Beaverton, Oregon)</u>

- **Founded 1999;**
- **48 employees (40% PhD, 80% Advanced Degree)**
- **Vertically integrated 3D Imaging Capabilities**
  - Avalanche Photodiode (APD) and PIN detectors and arrays
  - Readout Integrated circuits (ROICs)
  - Active & Act./Passive Focal Plane Array (FPA) Manufacturing
  - Rangefinders, 3D Imaging, LADAR, and Electro-Optic Systems
- **Light manufacturing, micron-scale assembly, and class 100 cleanroom**

<u>Voxtel Nano (Eugene, Oregon)</u>

- **Nanotechnology Products Group *(Sold to Shoei Chemical 2003)***
- **Nanocrystal Detector Products**
- **Analytical Facilities (HRTEM, SIMS, XRD, UPS/XPS)**

<u>Vadient Optics (Corvallis, Oregon)</u>

- **Spun out in 2013; Inkjet Solid Freeform Fabrication of GRIN Optics**
- **70% PhD**

Voxtel is a Vertically-Integrated 3D Imaging Company

PD and APD Die and Arrays → ASICS → FPAs & Hybridization → Opto-mechanical Packaging → OEM Modules → Subsystems

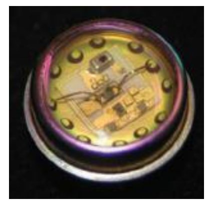
Photodiodes, APDs & Arrays

High Gain, Low Noise APDs

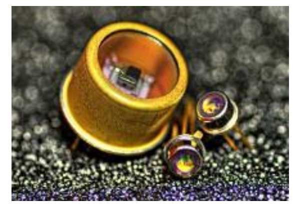
Segmented Detectors

Back-illuminated APD arrays

Photoreceivers

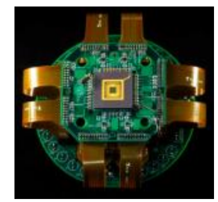


20MHz to 2.5 GHz TO8 Receivers



Hermetic and Multi-stage TEC cooling

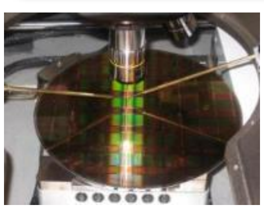
LIDAR/LADAR RECEIVERS:
Event-driven TOF/Amp. & Full Waveform



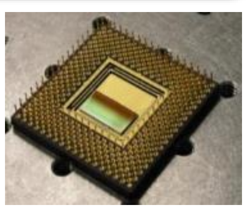
Time & Amplitude Full waveform

< 30 ps, 1024 channel time-to-digital converter with TOT

ROICs
Photon Counting & Event Driven /FPAs

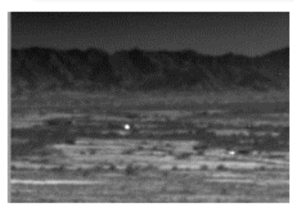


Sparsified, event driven amplitude or arrival time



Asynchronous Event-driven photon counting

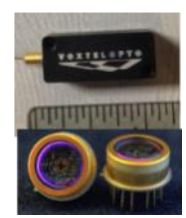
Active/Passive FPAs
NIR/SWIR & SWIR/MWIR



Seespot & Timespot with asynchronous laser TOF and PRF

Transient MWIR detection and & MWIR Passive

Laser Rangefinding Technologies

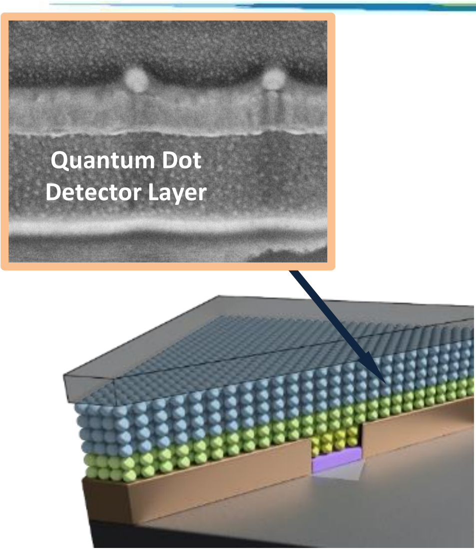


Rx/Tx Components

OEM Modules

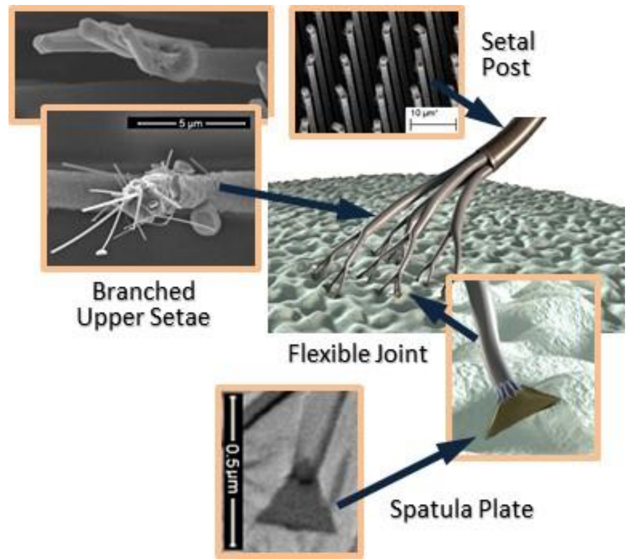
Eyesafe Rangefinders

Voxtel is a Leading Nanotech Research Team

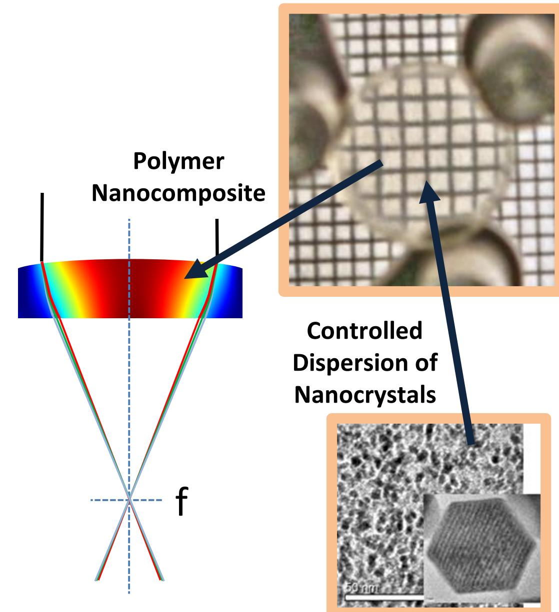


Functionalized CMOS Sensor Pixel

DARPA Wafer-scale Infrared Detectors (WIRED): Room Temperature SWIR and MWIR High Resolution Imaging



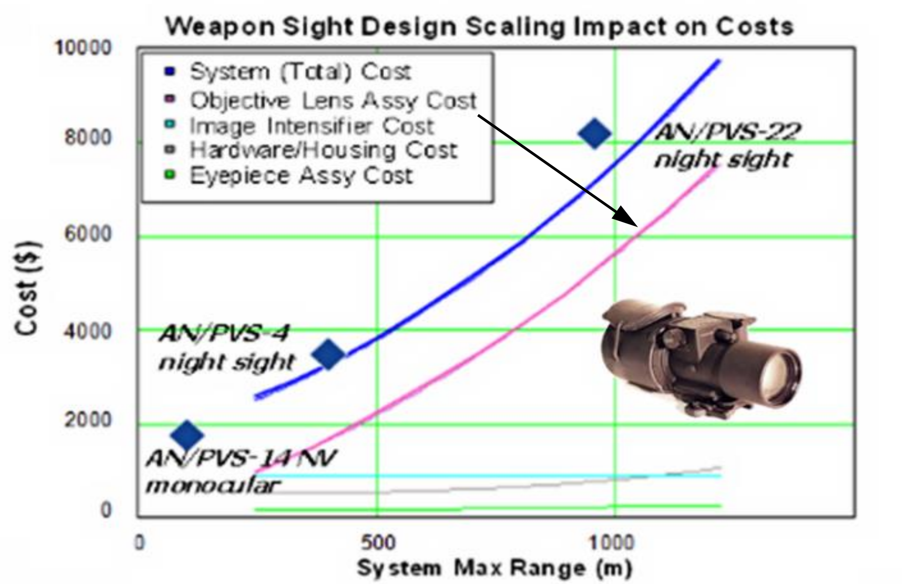
DARPA Atoms2Products (A2P): Demonstration w/Gecko Setae Structure Replication



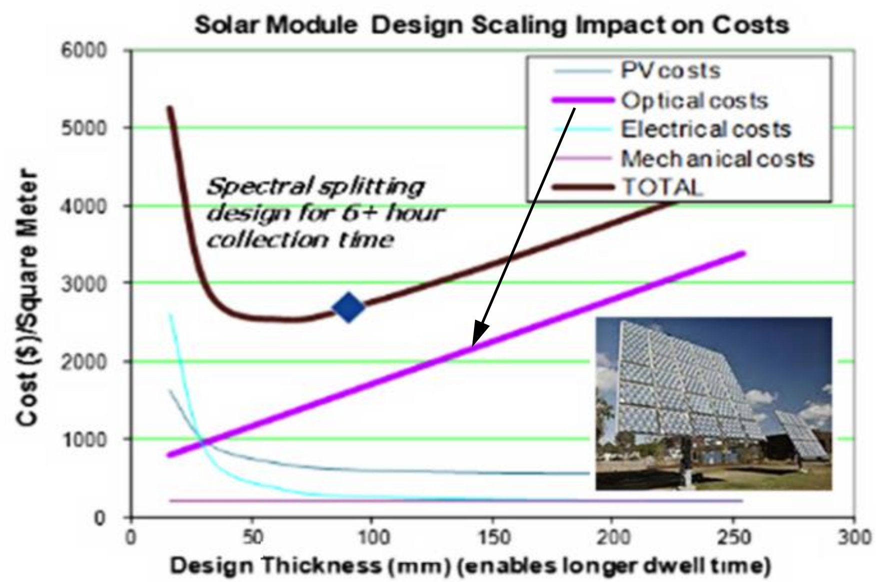
DARPA Manufacturable Gradient Refractive Index Optics (MGRIN): 3D Freeform GRIN Lenses

- **Voxtel, Inc is executing and has executed competitive DARPA BAA programs to:**
  - **Bring SWIR-MWIR imaging to low cost applications**
  - **Develop practical multi-scale multi-material assemblies, angstroms to microns**
  - **Create a manufacturable free form GRIN optics process**
- **This team has developed a lenslet array for the NASA PISCES integral field spectrometer (IFS) exoplanet exploration system**
- **We have executed dozens of other quantum dot research programs with government and corporate collaborators**

Problem: Optics Dominate Electro-optical System Costs



Military and High Performance Imaging and Direct View Optics

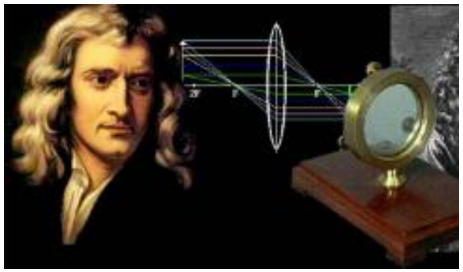


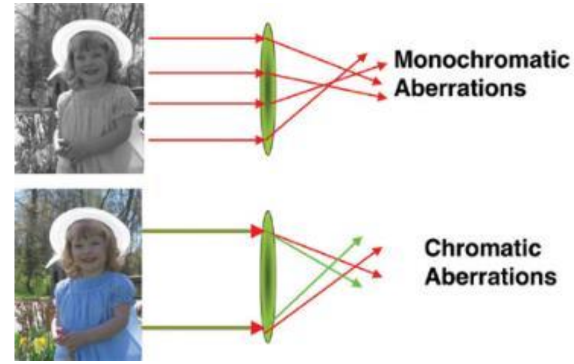
Photovoltaic Concentrators

As energy or information requirements increase, systems are limited by the size, weight, power, and cost of optics

Canon CN-E 14.5-60mm T2.6
Price: $42,750.0

Refractive Optics Design Has Not Changed in a Millennium





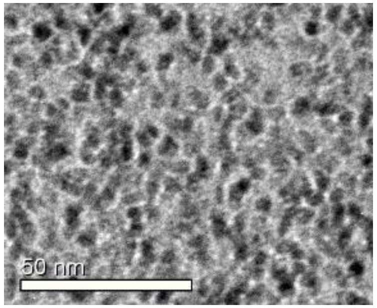
- **Every component of an EO system has become lighter and smaller EXCEPT the optics**
- **High-performance electro-optical system cost, size, and weight is driven by optics**
  - Conventional lenses w/limited degrees of freedom produce aberrations
    - Requires large # of lenses to achieve needed design freedom
  - Glass melts used to create blanks that must be ground and polished
  - Designers use assemblies of stock lenses because custom optic lead times are measured in months and NRE costs usually far exceed the total optic order
  - Alignment of many lenses requires complex mechanical assemblies
  - Complex optic alignment and temperature stabilization dominates costs
- **Optics costs are too high for future light emitting and detecting product markets**
- **Custom freeform and aspheric lenses have long lead time and high NRE**
- **Plastic optics have birefringence, poor performance, and poor tolerances**

Voxtel's Additive Manufactured Optics: VIRGO

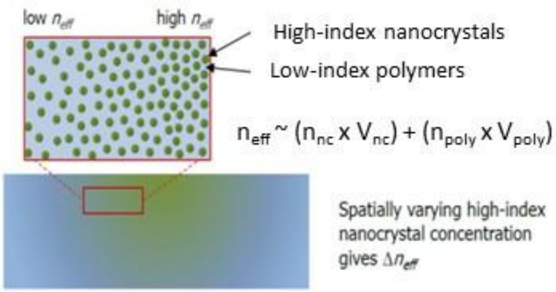
Volumetric Index of Refraction Gradient Optics (VIRGO)

- **Additive manufacturing (AM) via drop on demand inkjet print fabrication of GRIN optics**
- **Nanocomposite inks used to print volumetric optical index gradient (3D GRIN) elements**
  - Nanoparticles in polymers => high index (n_λ) optical inks
  - Change in nanoparticle concentration on substrate creates optical index contrast (Δn_λ)
  - Mixing and diffusing droplets on substrate creates optical index gradients (Φn_λ)
  - Two or more nanoparticle materials provide control over chromatic dispersion, v_d
  - Relative change of concentrations of two nanoparticle materials controls V_{GRIN}
- **Cured optics implement complex, freeform optical functions**

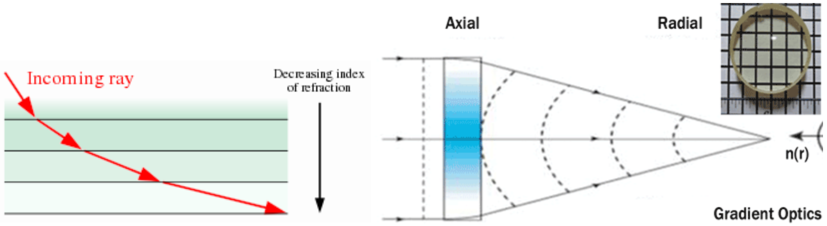
Multi-head optical printer



Optical Inks composed of nanoparticles in monomer



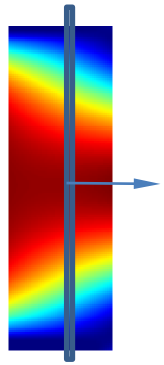
Nanofiller concentrations create index gradients



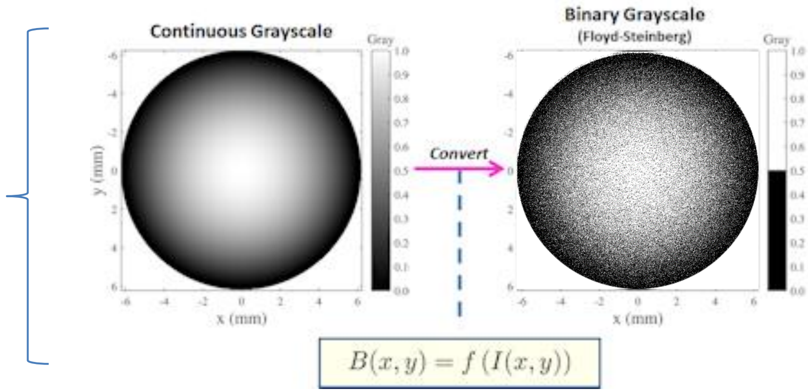
Optical functions implemented in planar films

VOXTELNANO

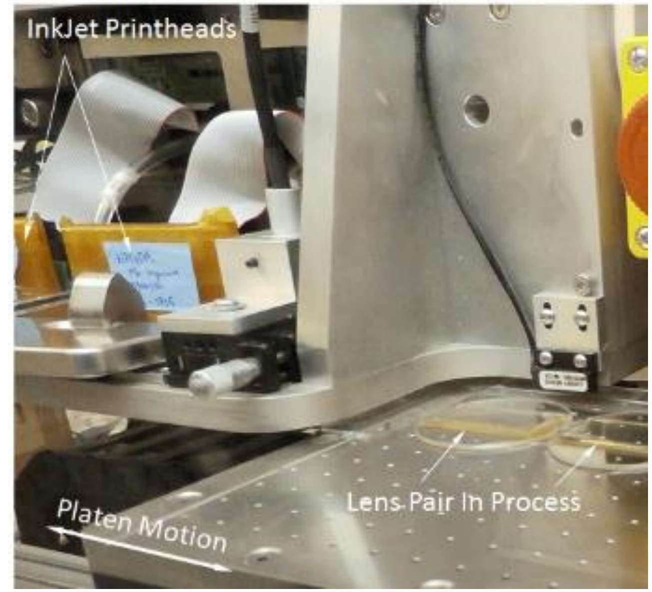
VIRGO Ink Jet Print Fabrication



3D Freeform GRIN Design (f5 lens)



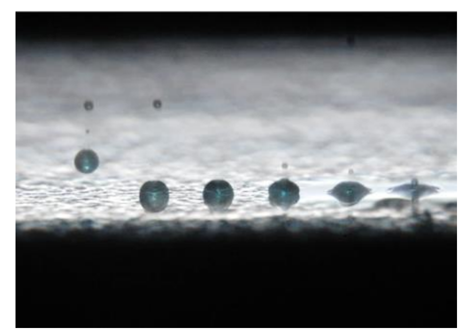
Conversion from continuous to voxelated bitmap for printing



Custom R&D Multi-head Ink Jet Print Platform

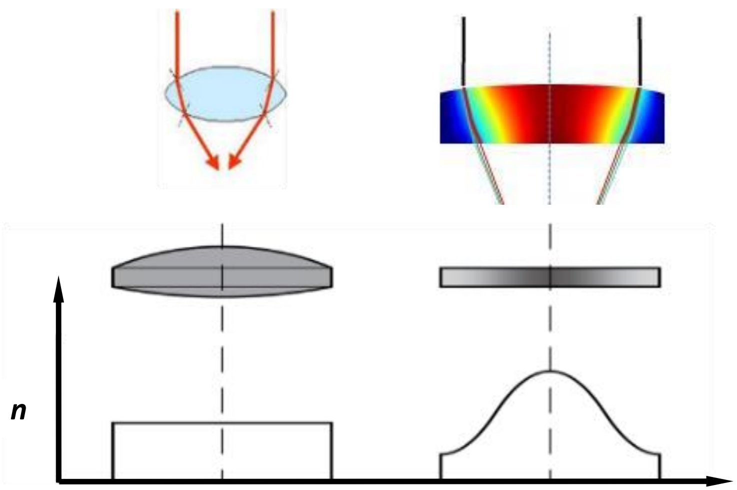
Fabrication process

- Design parameter(s) chosen
- 3D GRIN profiles selected based on optimization
- Nanofiller concentration profiles developed based on:
  - Nanoparticle diffusion
  - Number of inks used
    - Binary or multi-level optical index levels (grey scale)
    - Multiple spectral characteristics (Abbe number)
- Error diffusion halftone algorithm used to convert design to binary or multi-level bitmaps

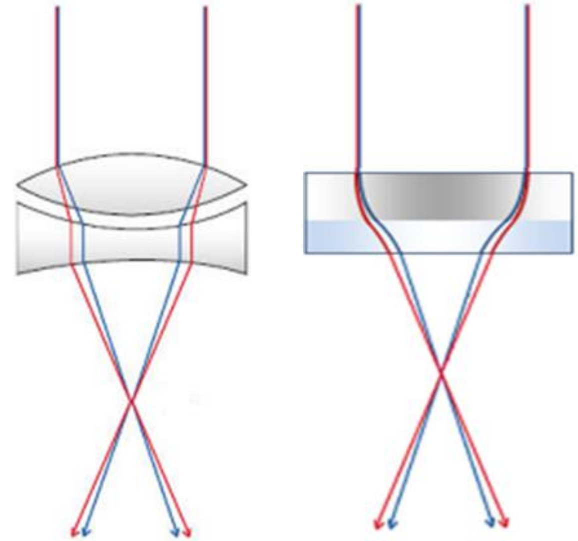


Droplets on Substrate

VIRGO AM GRIN adds new degrees of freedom



Converging lens made of homogenous index | *Converging lens made of gradient index*

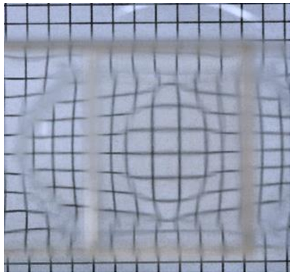
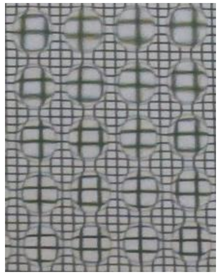
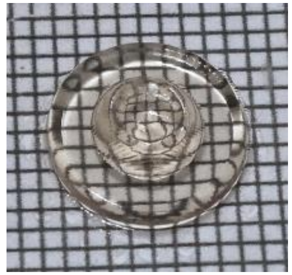


Traditional achromatic crown and flint doublet (left) and VIRGO one piece printed plano lens (right)

Voxels of nanocrystal-polymer composite optical ink feedstock - selected from within design polynomials – are printed throughout lens to create freeform optical index patterns

- **In multi-lens optical systems, reduces required lenses**
- **AM dramatically reduces (~100x) time required to execute an optic design**
- **<u>Ability to manufacture *non-radially symmetric* optical elements</u>**

VIRGO is a Complete Solution

3D Freeform VIRGO Optics

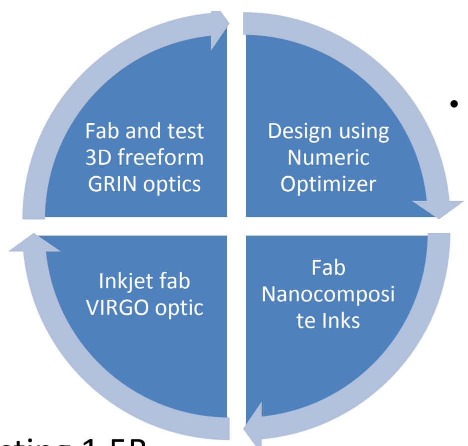
- printed directly from CAD
- flat GRIN lenses realize complex optical functions – that can correct chromatic and geometric aberrations

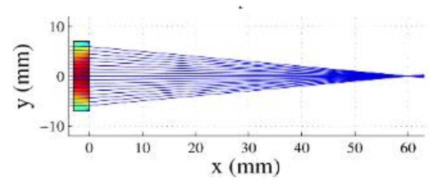
Custom Multi-head VIRGO Inkjet Fabrication Platform

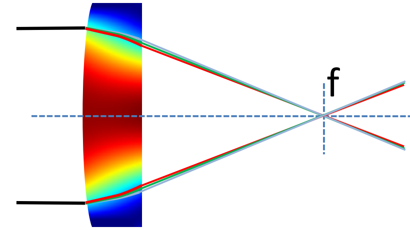
- Sub-micron alignment of ink drops
- 6” x 8” x 1/2 “ is current capability
- Scales to production quantities using existing 1.5B drop per second commercial print heads

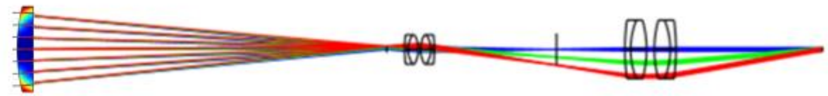


24 Hour Turn Time







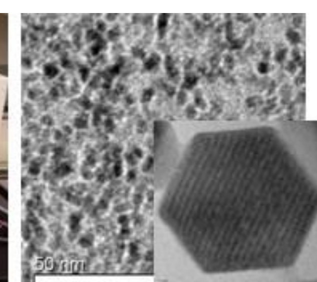


VIRGO Design Tools

- ZEMAX, Code V, etc., TCAD tools have inadequate degree of freedom
- VoxOpt software numeric optimizer develops designs based on multiple criteria (spot size, wavefront, cost, dispersion, etc)

Automated Continuous Flow Nanocrystal Production

- Capable of < 5% size, phase, shape variation
- Scales to kg/hr production rates
- Feedback monitoring and process control

VIRGO Productivity Scales via Nozzle Count

Custom Vadient R&D Printer, Dimatix Inkjet Printheads (2013)

64 nozzles
1 & 10 pl; 10 khz; 4 inks
0.00064 Billion voxels/sec
Fabricates 1 benchmark lens/week

HP FB550 (2005)

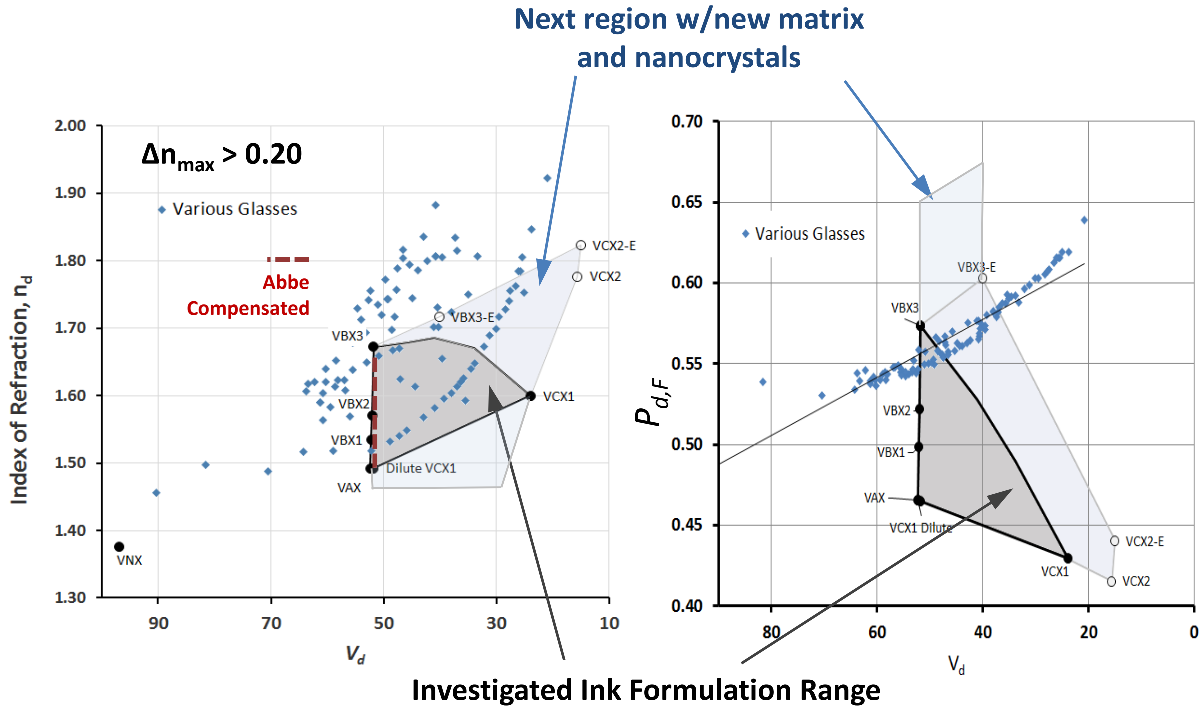
2,304 nozzles
15 pl; 20 kHz; 6 inks
0.40 billion voxels/second
Can fabricate ~100 benchmark lenses per hour!

HP Web Press (2014)

2,100,000 nozzles
150 billion drops per second
Array of arrays can fabricate ~45k lenses per hour!

- **Scalable by parallelization of: nozzles, print heads, and systems**
- **Current R&D printer has 64 nozzles in 4 printheads, generates 0.00064 Billion voxels/sec, and 1 benchmark lens in 3 weeks**
- **We are currently bringing up our VIRGO process on our FB550 printer**
  - **Delivers 100 benchmark lenses per hour**
- **Key research is in creating the variety of nanocomposite feedstock (inks)**
  - **Well underway**

VIRGO Nanocomposite Optical Inks Fill In Glass Chart

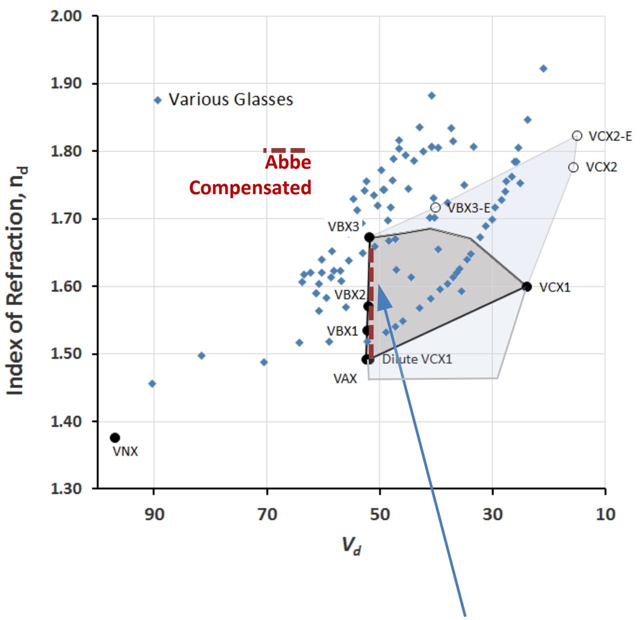


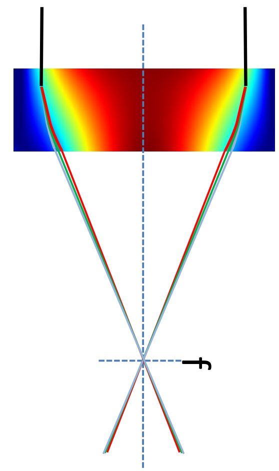
Index of Refraction vs. Chromatic Dispersion [Abbe # (V_d)], blue squares are glass optic materials

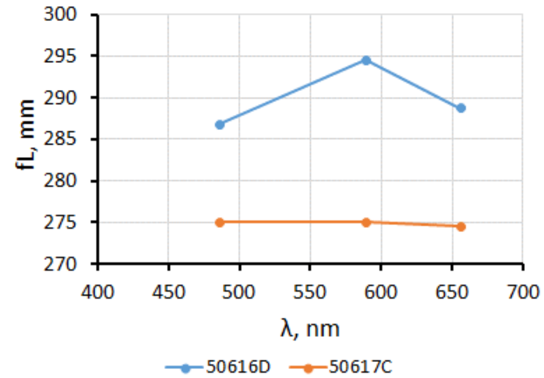
Partial Dispersion vs. Chromatic Dispersion [Abbe # (V_d)]

- **Extensive characterization of lenses with Voxtel inks VIRGO-RI-VAX, VIRGO-RI-VBX, and Dilute VIRGO-RI-VCX1 in 2015 - 2016**
- **Can place an ink within the grey shaded regions of the glass chart**
- **Lens printed with inks of $\Delta n = 0.10$ in 2016, $\Delta n_{max} > 0.20$ is possible**

Chromatic Dispersion Solution Demonstrated







Spectral Characteristics of Compensated and Uncompensated VIRGO Inks

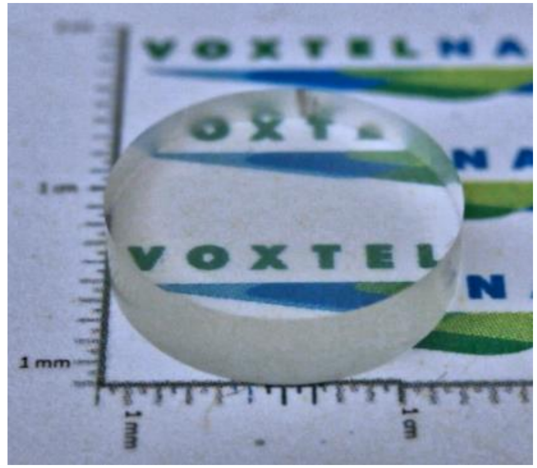
- **Path length of different wavelengths of light are controlled using mixtures of two nanofiller materials**

First Ever Achromatic Monolithic Lens Fabricated and Tested

Ink Type	Uncompensated	Chromatically Compensated
Part Number	50616D	50617C
High ink	VIRGO-RI-VBX	VIRGO-RI-VBX
Low ink	VIRGO-RI-VAX	VIRGO-RI-VCX_L
Chromatic shift	3.84%	0.18%
Measured f/df	37	550
Δn_{486} =	0.02895	0.03260
Δn_{589} =	0.02819	0.03260
Δn_{656} =	0.02875	0.03266
GRIN Abbe No.	144	549

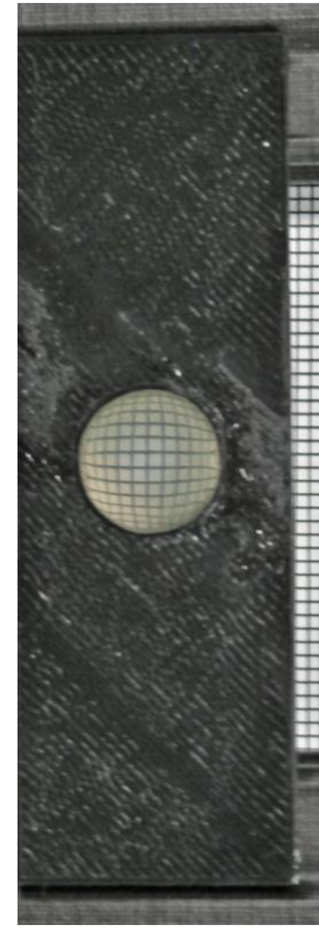
Wide Range of AM Optics Demonstrated

100 mm Phase Corrector Plate

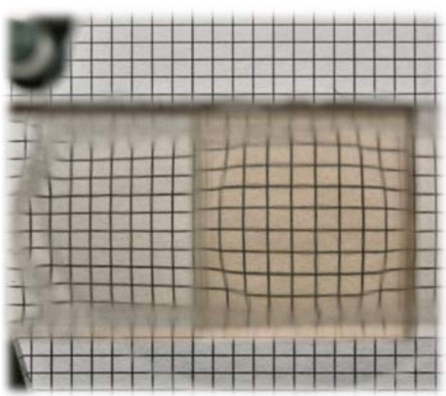


Plano-Plano-GRIN 12 mm f9 Lens

+/- Lens

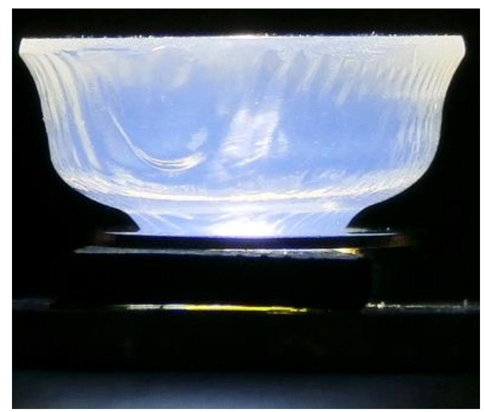


Lens in FDM Frame



GRIN Alvarez Lens Pair

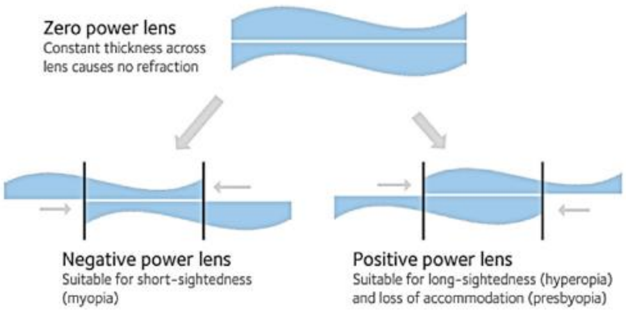
Plano-Convex-GRIN 6 mm Elastomeric Lens



3D LED Concentrator

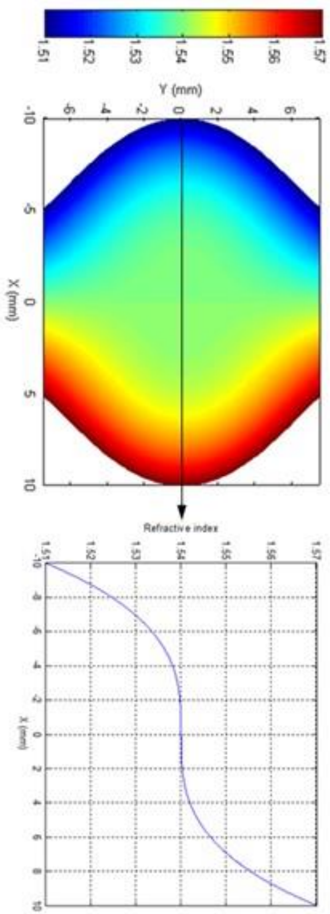
- > 1,000 parts printed, designed & built in 100 to 0.00017 mm lens configurations
- > 30 optical inks to vary index *n* in 3D, vary *n* w/voltage, or vary *n* w/intensity

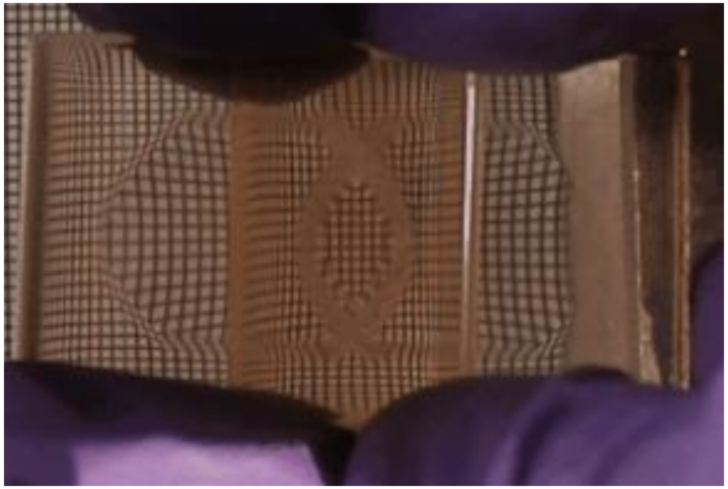
Alvarez Lens Pair for Variable Optical Lens Power



Homogenous Material Alvarez Lens Pair

Alvarez lenses to correct eye relief in respirator masks



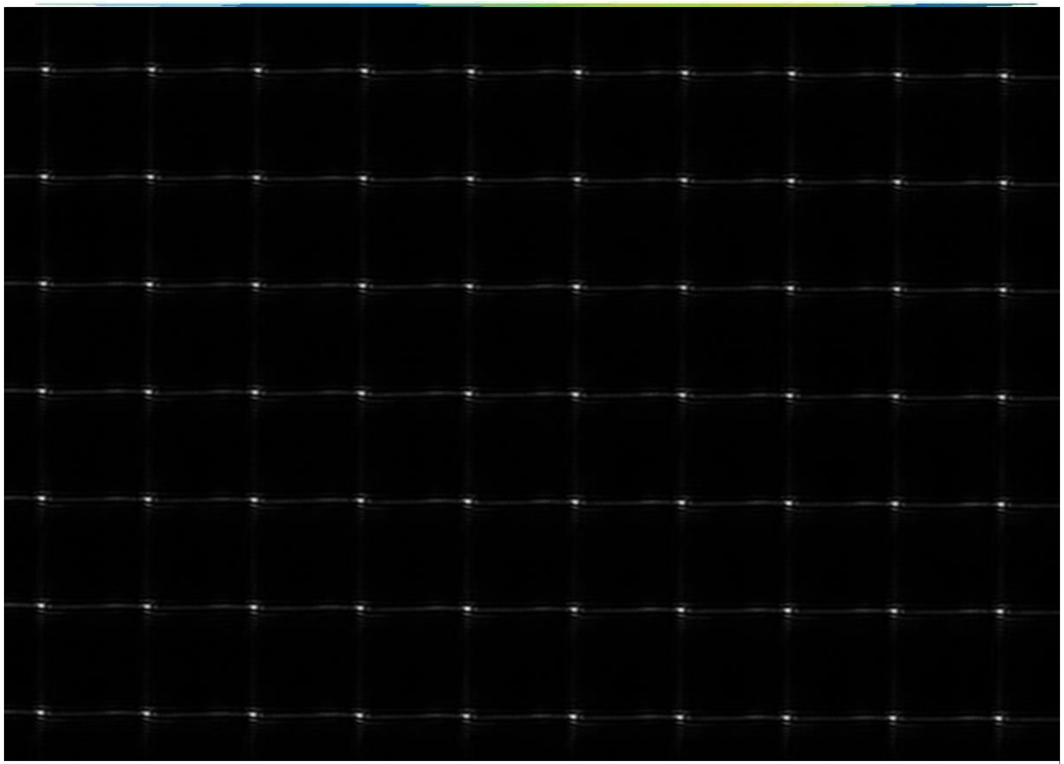


GRIN Alvarez Lens Pair Prototype

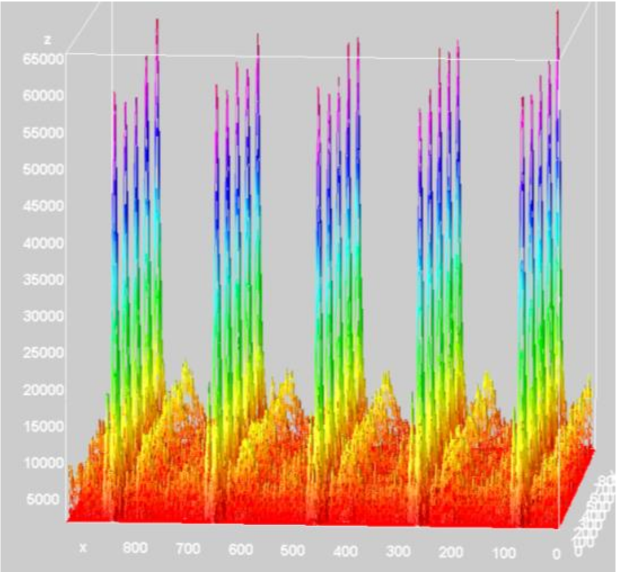
- **3D freeform optic VIRGO demonstrated creating Alvarez**
- **Manufacturing the required cubic index profile is possible with Voxtel's VIRGO process**

First Ever GRIN Alvarez Lens

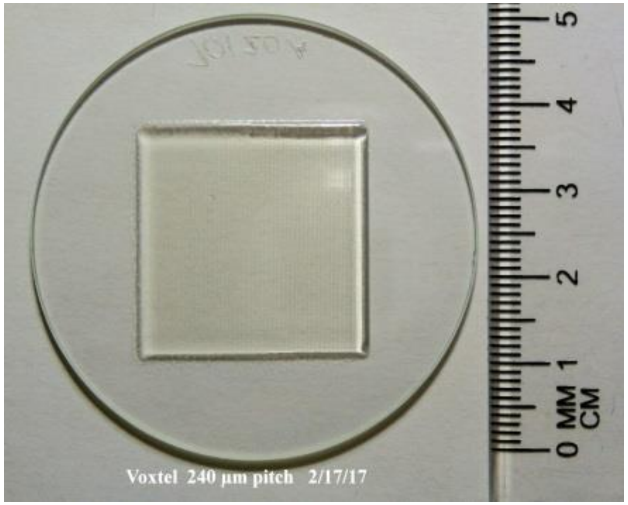
Micro-lens Array for NASA Exoplanet Research



PSF for Sample 70303A



Surface Plot of 70303A, 160µm dia, fL 0.86mm



160 µm pitch 26,569 lens array on a 2 inch substrate

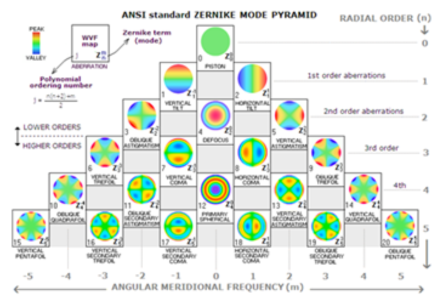
163 x 163 array of 160 µm pitch lenses created with 1 pL drops of optical ink

F3.8 with f_l = 0.86

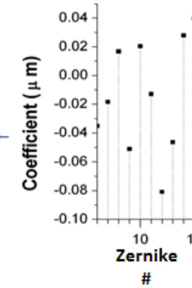
Excellent lens to lens uniformity over entire part

45-mm Phase Corrector Plate

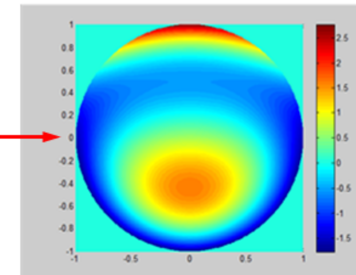
45 mm phase corrector plate on an optic flat



Zernike Polynomial Terms

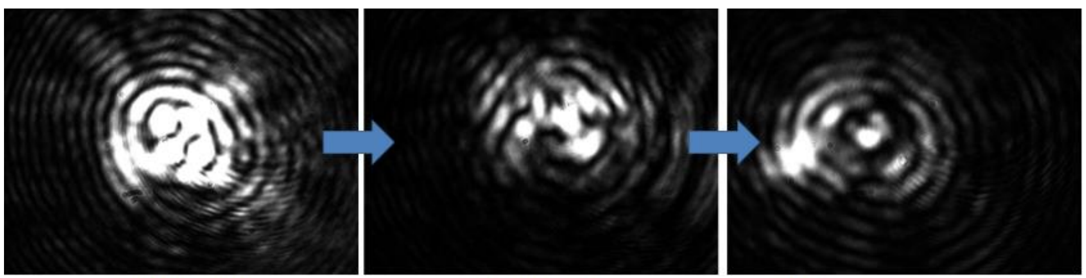


Term Combinations



Combined OPD correction plate

Defining Phase Correction



Without PCP | With PCP 41031F | With PCP 41031F and offset

Focus for LA1301 lens w/o compensation (left), w/PCP (middle and right)

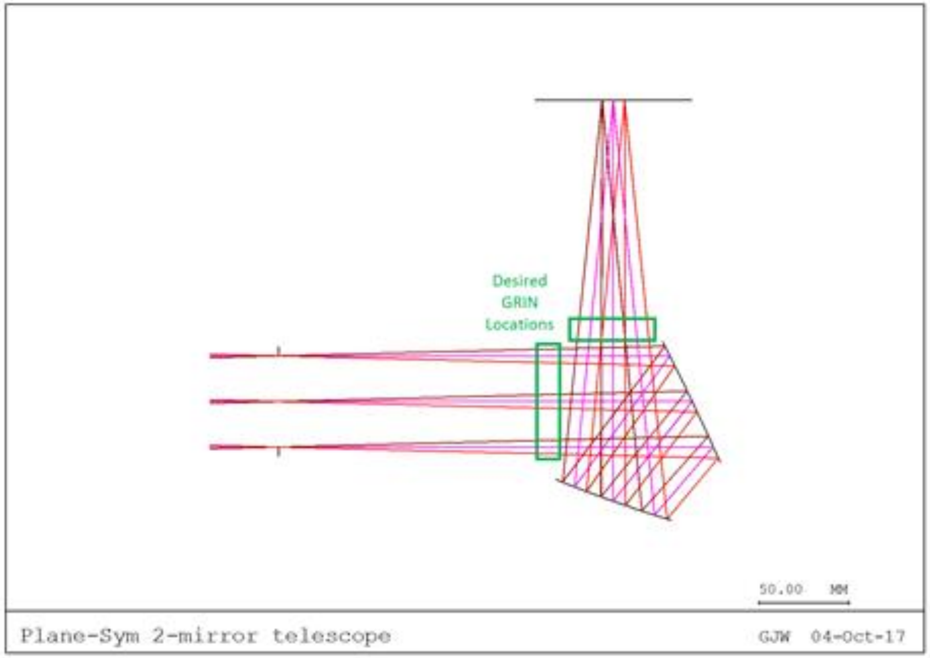
UV stimulation to show nanoparticle concentration gradient

- **Saddle functions are commonly represented with Zernike polynomials, as with this 45 mm phase corrector plate**
- **Corrects aberrations in lens and telescope optics**
  - 80% of the way to diffraction limit
- **Printed overnight from Zernike polynomials**

First GRIN Phase Corrector

NASA freeform GRIN optic for aberration correction

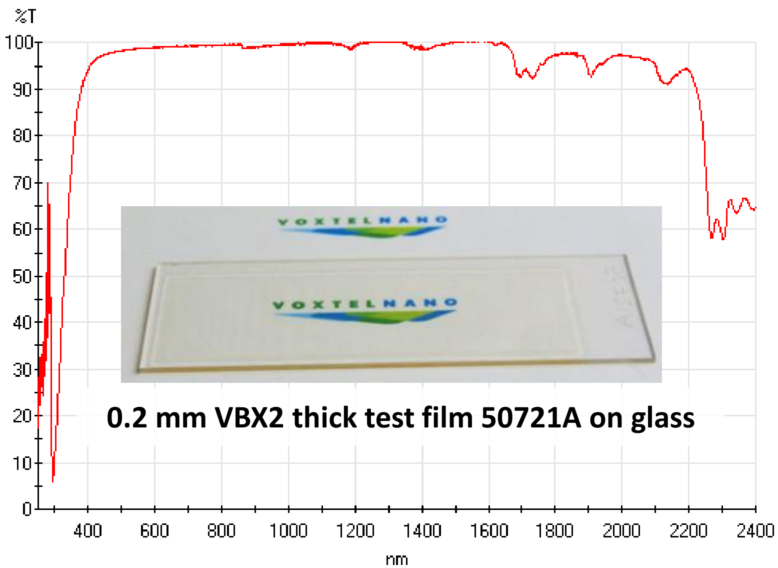
Freeform GRIN phase corrector

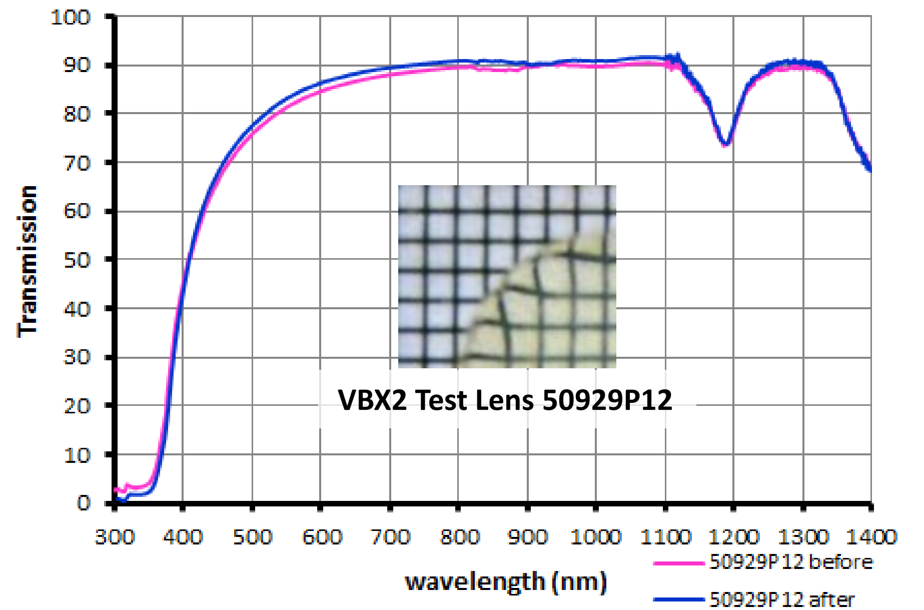


Two-mirror freeform design used in GRIN design study

- **Investigate freeform GRIN optics in a compact two-mirror freeform designed for CubeSat**
- **Understand effectiveness of a GRIN element at wavefront correction in this type of system**

Excellent Light Transmission VIS to NIR, Stable in Environment



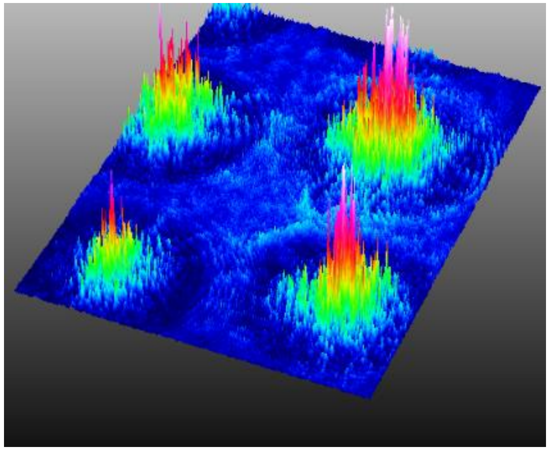


Transmissivity % vs λ for 0.2 mm VBX film

Raw Transmission % vs λ for 3 mm test lens in Mil-Std 810G

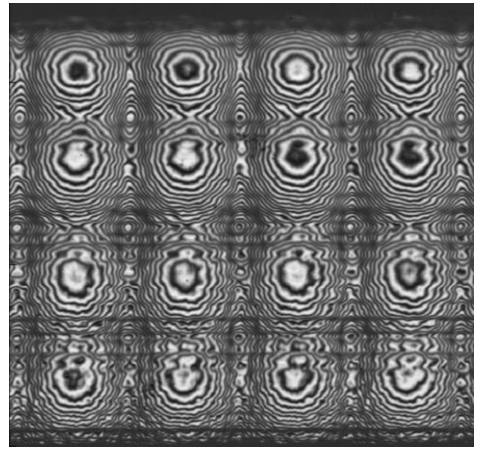
- **Voxtel's optical inks consistently show excellent light transmission – measurements shown are not corrected for thickness**
- **No difference in UV-VIS-NIR transmission of printed 3mm thick GRIN lens 50929P12 before and after Mil-Std 810G environmental test**
    - 7 day cycle: -30C/0% RH to +40C/90% RH @ Elemental Materials Tech, Hillsboro
- **No detectable mechanical changes – over 8 parts, thickness changed -0.017%**
- **1.5% difference in focal length measured between control and test samples**

Optical Power Over Time in VIRGO 3D Optics

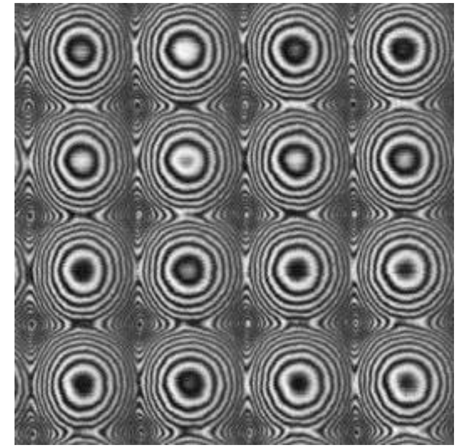


NOV 2013 – First lens – 1.7 m fL

Δn = 0.01

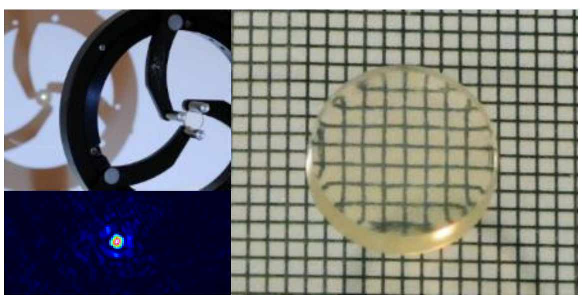


NOV 2014 – First f20 lens



MAY 2015 – Achromatic Lens

Δn = 0.03

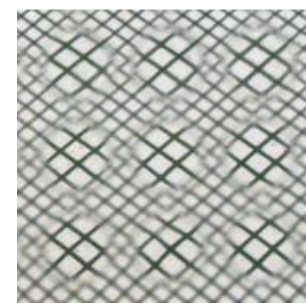


JUL 2015 – First Plano-Plano-GRIN f9 lens

FEB 2016 – 1st 30 mm

JUNE 2016 – 12 mm f5

Δn = 0.06

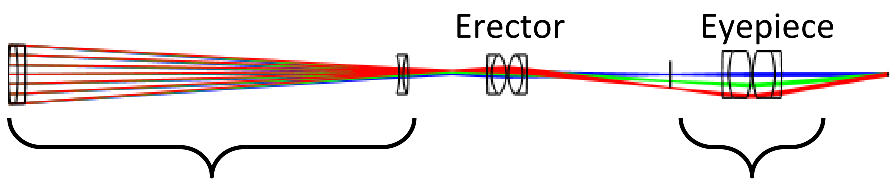


OCT 2017

0.6 Strehl

- Voxtel VIRGO Research Starts April 2012
- Achieved a wide range of 3D GRIN firsts over MGRIN program

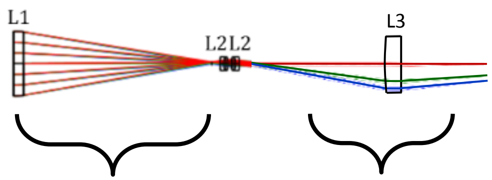
Scope Weight Reduced 50% With VIRGO GRIN Lenses



Objectives in telephoto
$(f = 243.35\ mm)$

Lenses in eyepiece
$(f = 39.2\ mm)$

Benchmark design - USP 3,612,646

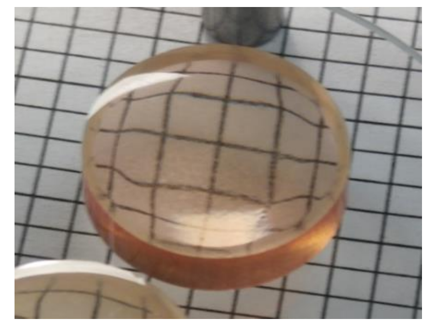


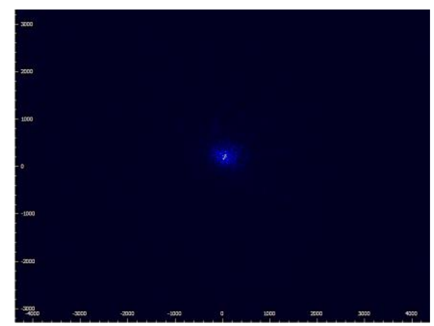
GRIN objective lens replaces 2 doublets (f = 90 mm, CT = 5 mm)

GRIN eyepiece lens replaces 2 doublets (f = 39.2 mm, CT = 7 mm)

Voxtel Design with GRIN lenses

Eye relief	~ 2 ¼ inch (~57 mm)
Exit pupil	~ 1.5 mm
Entrance pupil	~ 30 mm
Total length	267.7 mm (**42% reduction from 458.1 mm**)
Mass of lenses	11.7 g (84% reduction from 75.3 g)
Total mass	250 g (est) (**50% reduction from 500 g**)
Optical inks	VBX3/VNX; *Δn* = 0.22



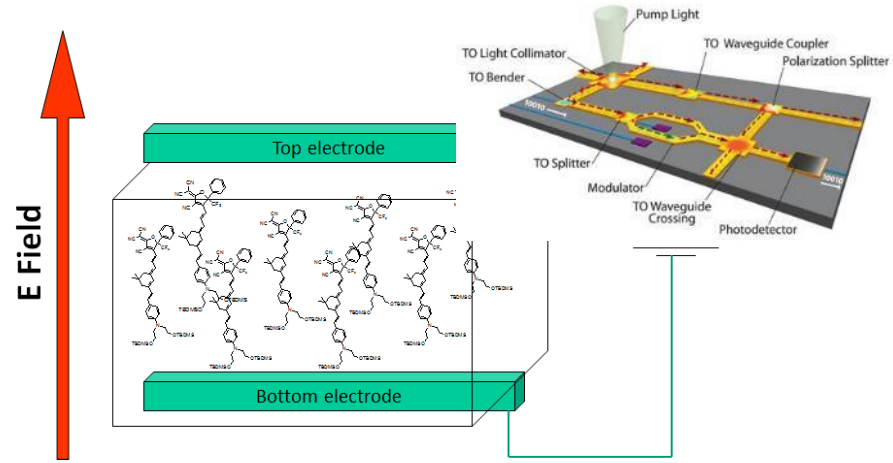


12 mm dia (plus border) lenses, VBX2/VCX1-L chromatically matched & diamond turned *f*5 lens, tight PSF

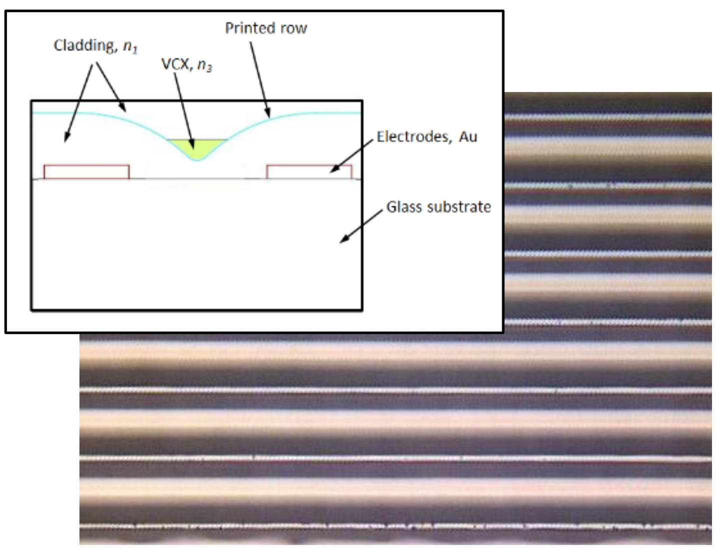
Ink Jet Printed VIRGO Electro-Optic (EO) Devices

VIRGO-RI-VEX: EO inks

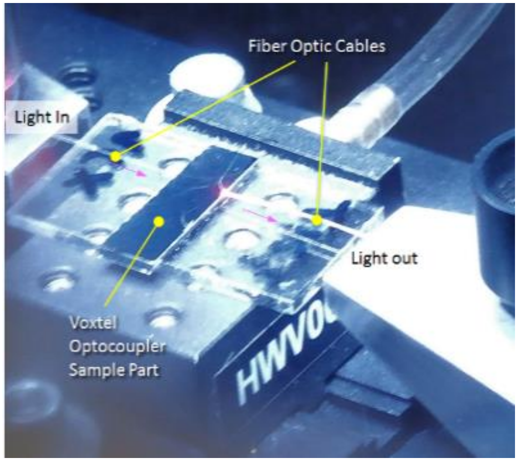
- 3D engineering of *n* <u>and</u> permittivity
- Active electro-photonic devices
- Pockel's Effect; r_{33} = 96 pm/V
- Δn = 0.008/(100 V/µm)
- EO nanocomposite active waveguide core



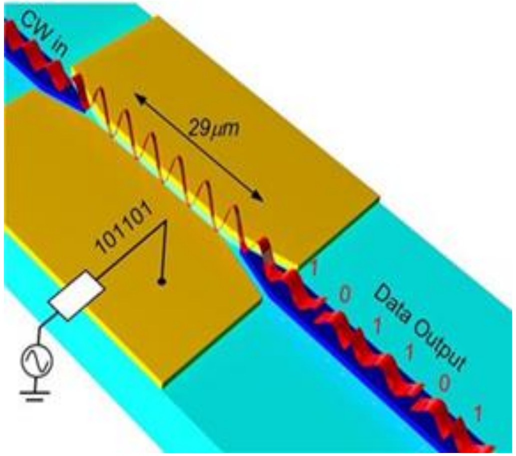
Altering n with V



Printed 5 µm waveguides



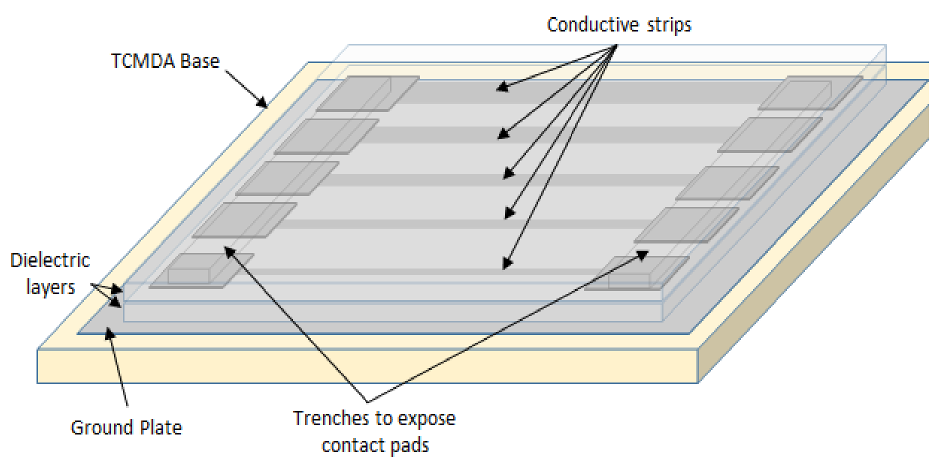
VIRGO Waveguide

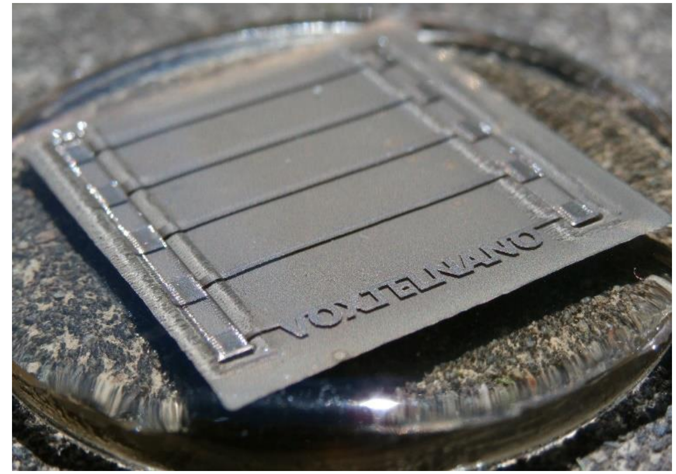


Phase modulator encodes information in phase of light

In addition to optics…

Electrons & Photons: VHX Sintered Silver NP w/VBX





Ground plane (4 µm thick), di-electric insulating layer (200 µm thick), patterned conductive traces (4 µm thick), di-electric cover layer with exposed contact pads (200 µm thick)

VIRGO-CN-VHX: Conductive Ink

- **Silver NPs, photo sinter to ~1/4 bulk conductivity**
- ***<u>VIRGO-RI-VBX compatible with 150 °C cure for 24 hours</u>***
- **Printed silver metal is reflective**
- **Compatible with optical printing**

Ghz antenna field for frequency selective surface under coverlayer, printed on VBX film with VHX silver nanoparticle ink

First High Conductivity Traces with Optics

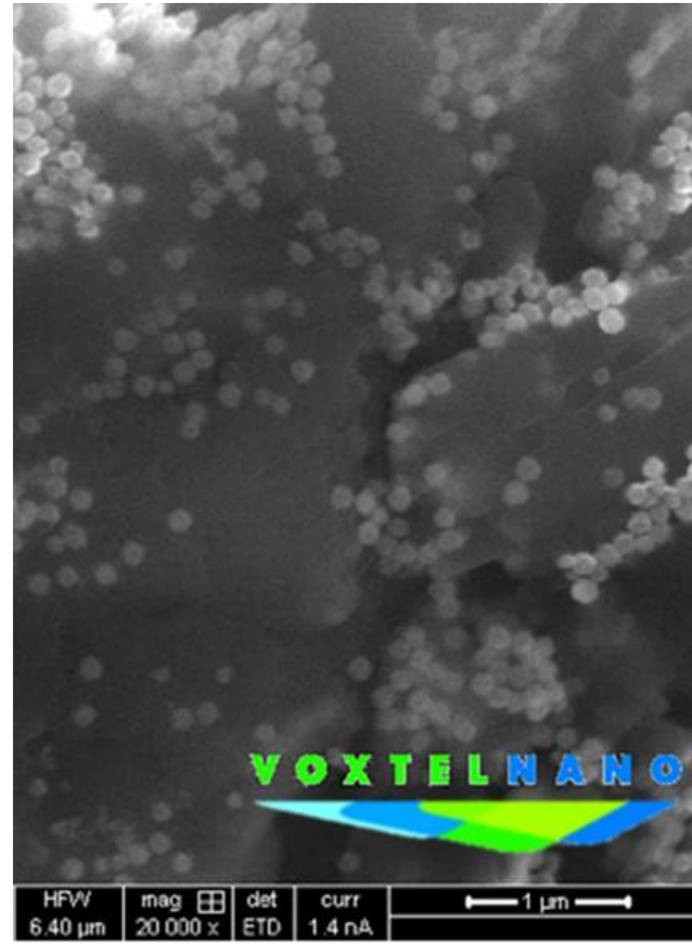
In addition to optics…

1st 3D Patterned Ink Jet Printed Magnetic Polymer

Electro-magnetic Inks

- 3D engineering of permeability and permittivity
- Have demonstrated free-space impedance match
- Soft and hard (low and high coercivity) demonstrated
- AM integrated motion sensing via hall effect
- AM 3D antennas, electric motors, latches, etc

Floating polymer moving to magnet, lifted by magnet



TEM image shows nanoferrites in polymer matrix at 66 wt% loading

First Gradient and 3D Printed Magnetic Polymer