Image Quality Criteria

Often used criteria:

Resolution : MTFs, Wavefront RMS, RMS spot size, Strehl Ratio, DPI……

Contrast

Color gamut,

Distortion

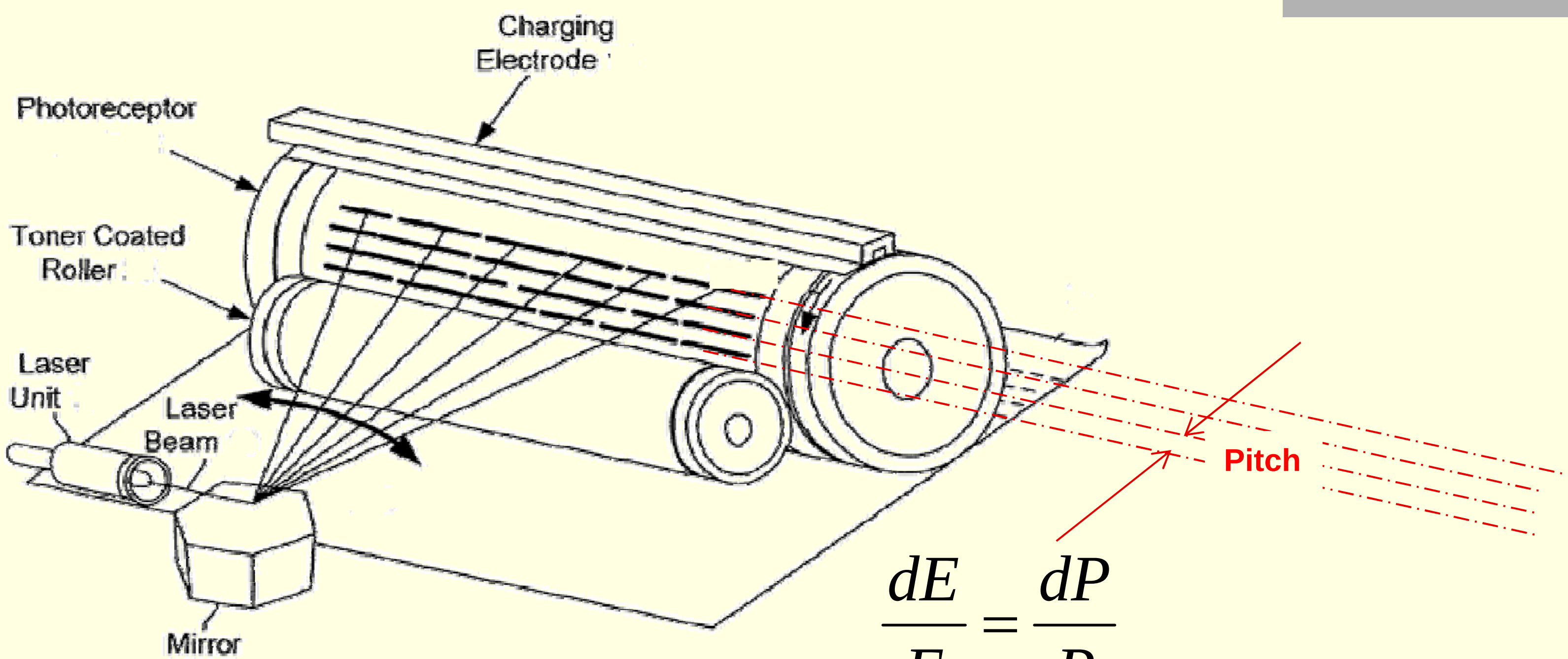
Noise….

However

Artifacts are important and need optical and/or electronic correction

Banding artifact - laser printing and projection

Laser printing and the "banding" artifact



$$\frac{dE}{E} = \frac{dP}{P}$$

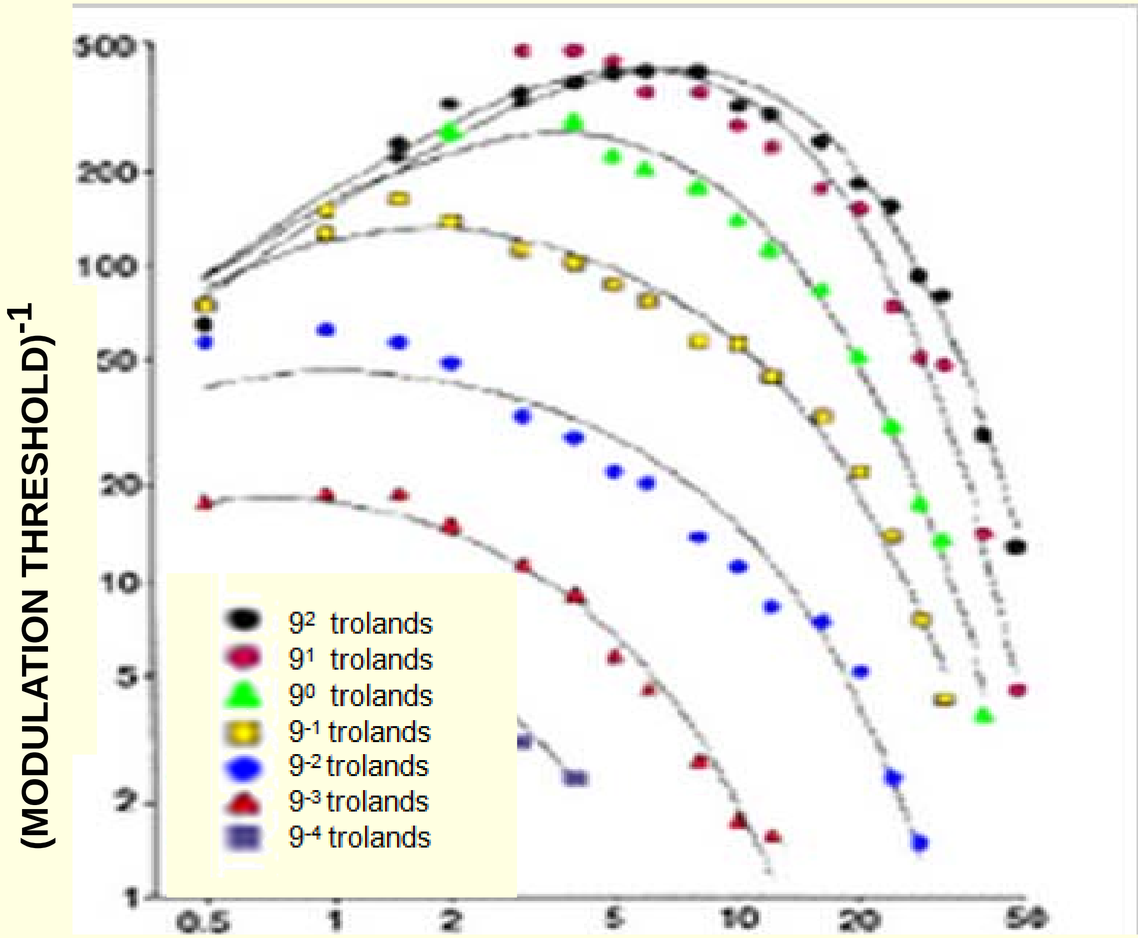
Where P is the pitch and E is the exposure

<u>The banding source:</u>

Polygon pyramid error.

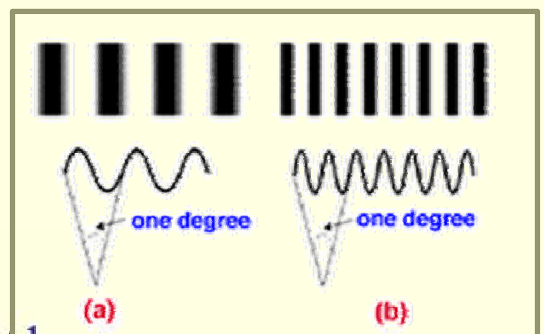
A 12 facets polygon will produce a modulation every 12 raster lines which will place it at the peak of the eye sensitivity curve.

Contrast sensitivity curve

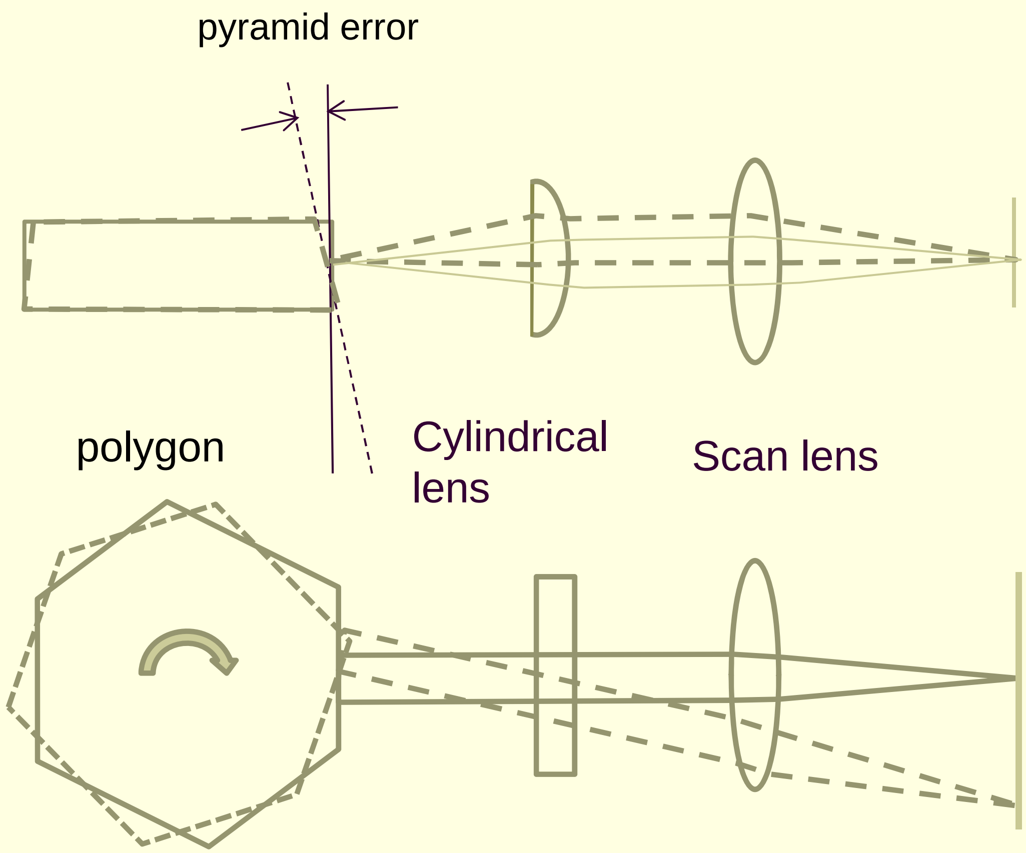


SPATIAL FREQUENCY (CYCLES/DEGREE)

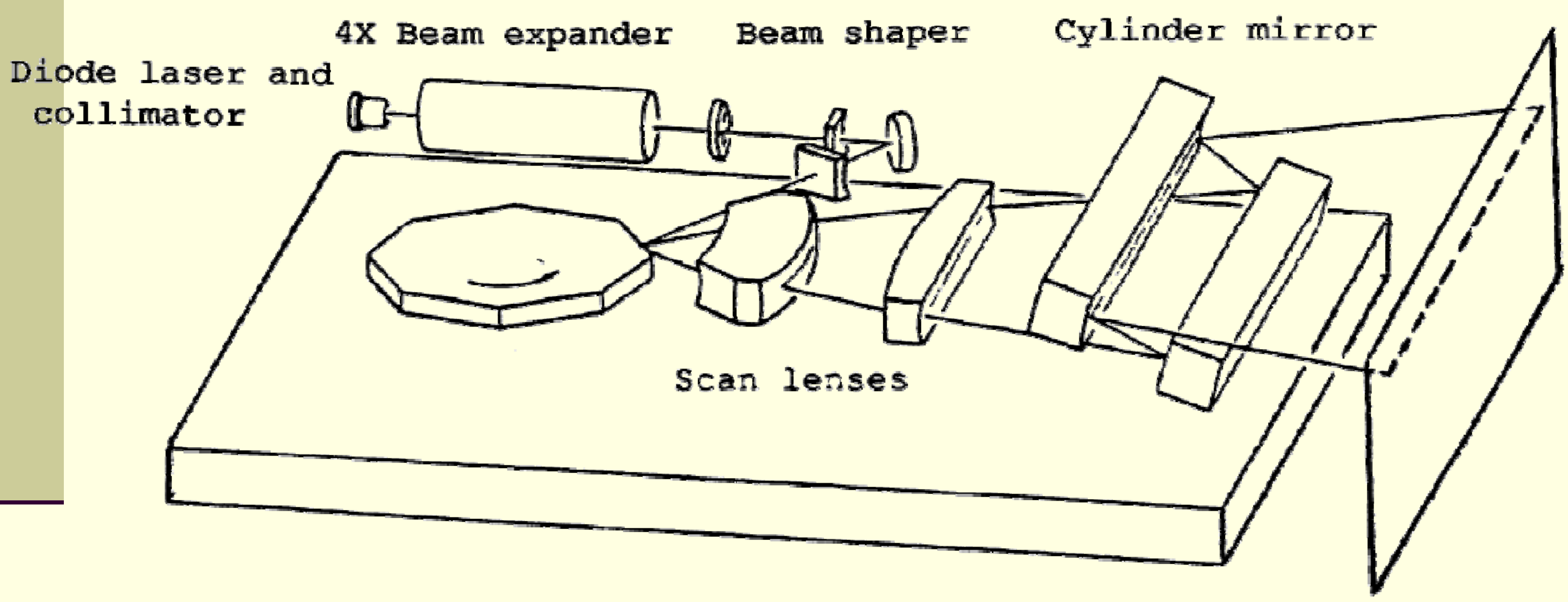
Curves are shown at different illuminance levels. From Van Ness and Bowmann data as in Cronly-Dillon , Visition and Visual Dysfunction, Lov 5. London, Macmillan Press 1991.



POLYGON PYRAMID ERROR CORRECTION BY CONJUGATION IS THE CROSS-SCAN DIRECTION

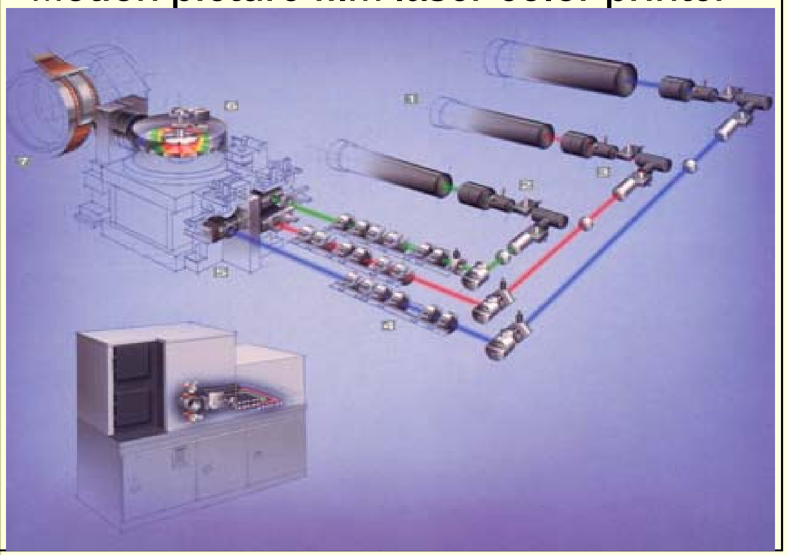


Optical layout of a high resolution laser printer

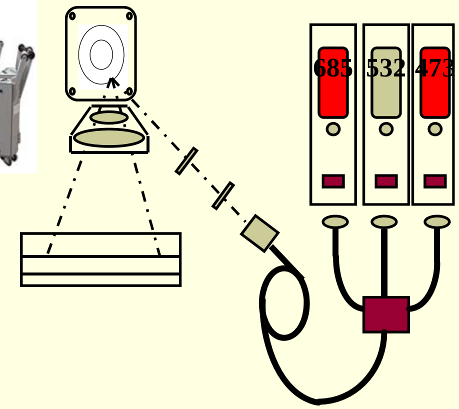


Continuous tone laser printers with pyramid error correction

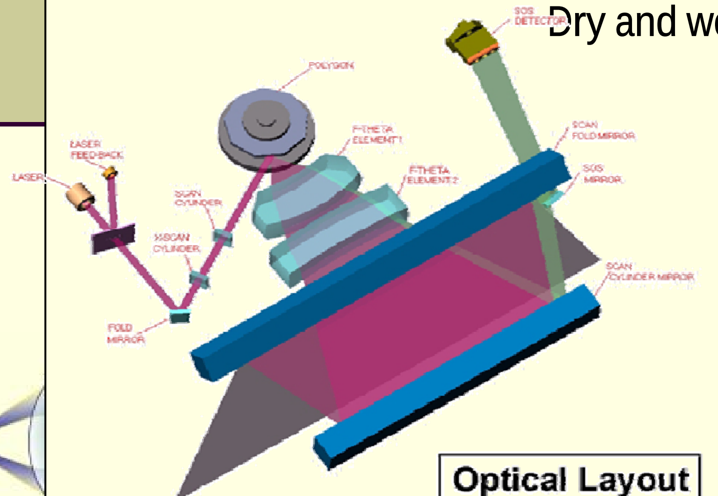
Motion picture film laser color printer

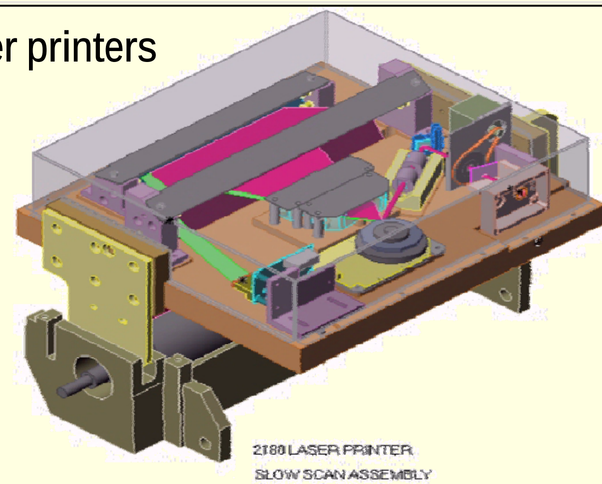


10,000 prints/hour photofinishing laser printer



Dry and wet medical laser printers



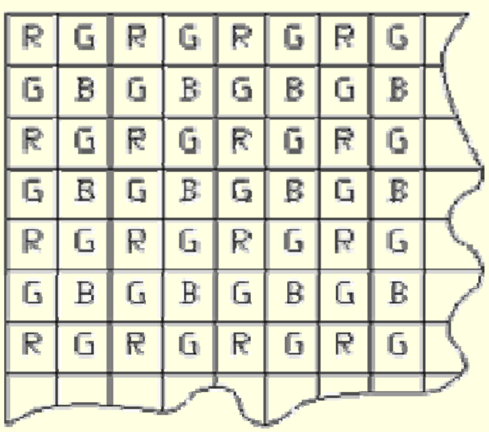


Aliasing and color aliasing

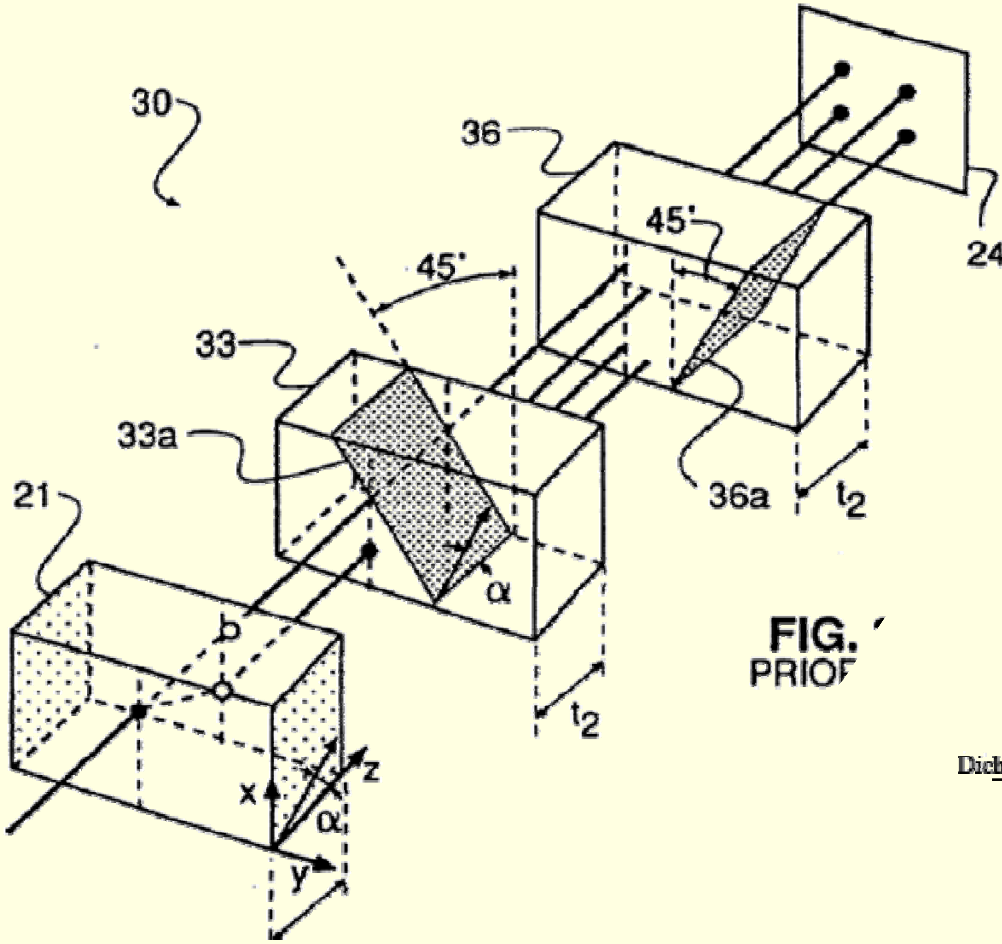
<u>Solutions for aliasing and color aliasing in digital cameras:</u>

- Do not under sample i.e. observe the Nyquist frequency.
  (for example: increase F/# when capturing)
- Use blur filters (= optical low pass filters= anti aliasing filters)
- Use mechanical dithering

Sensor Bayer pattern

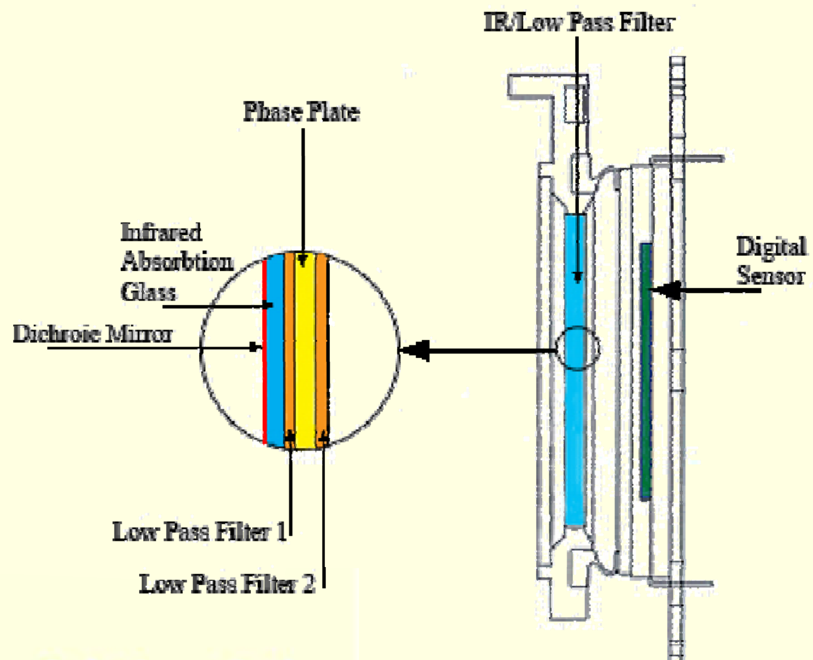


Anti aliasing filter: 4 spots

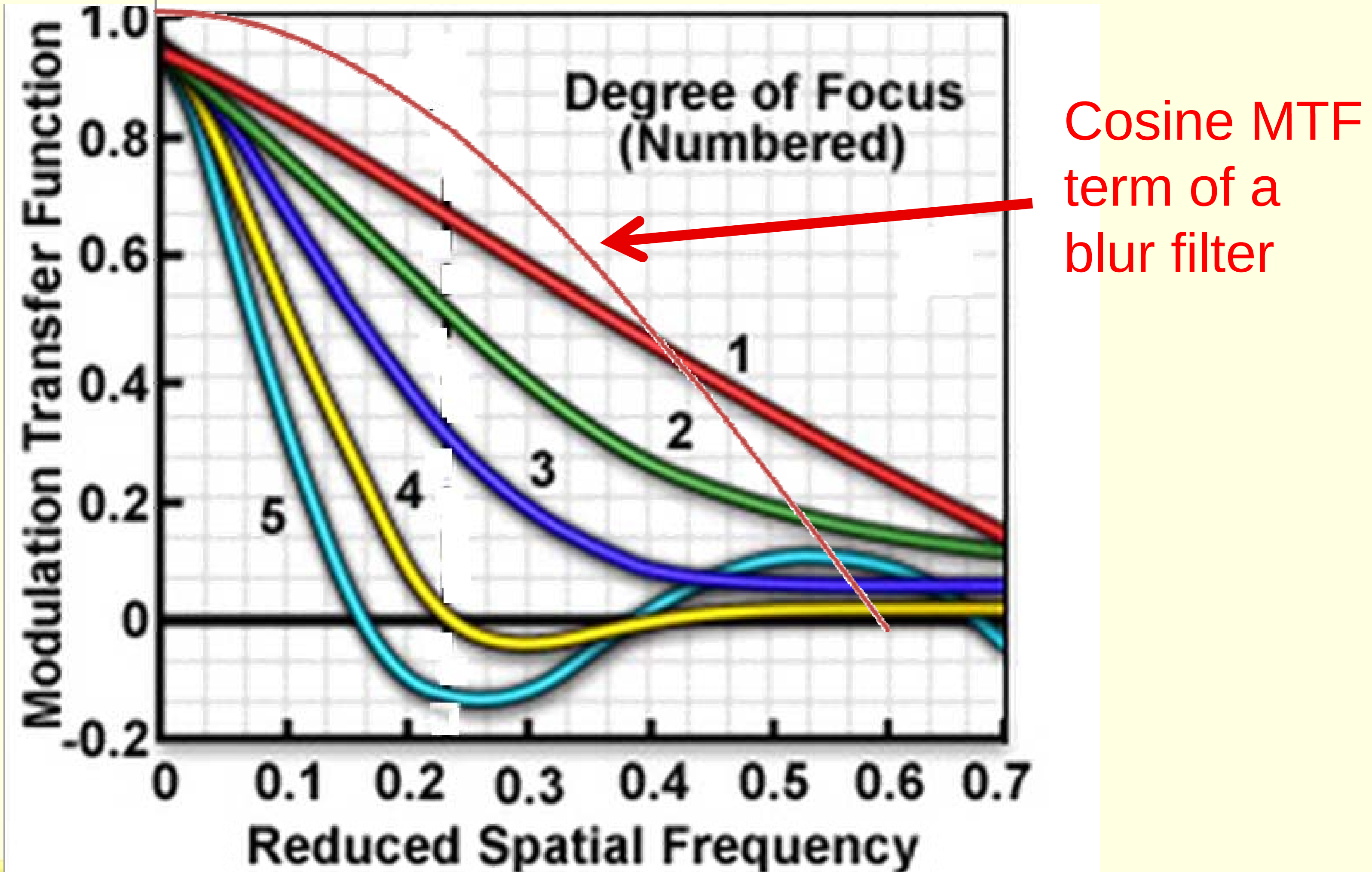


US 6,937,283 B1

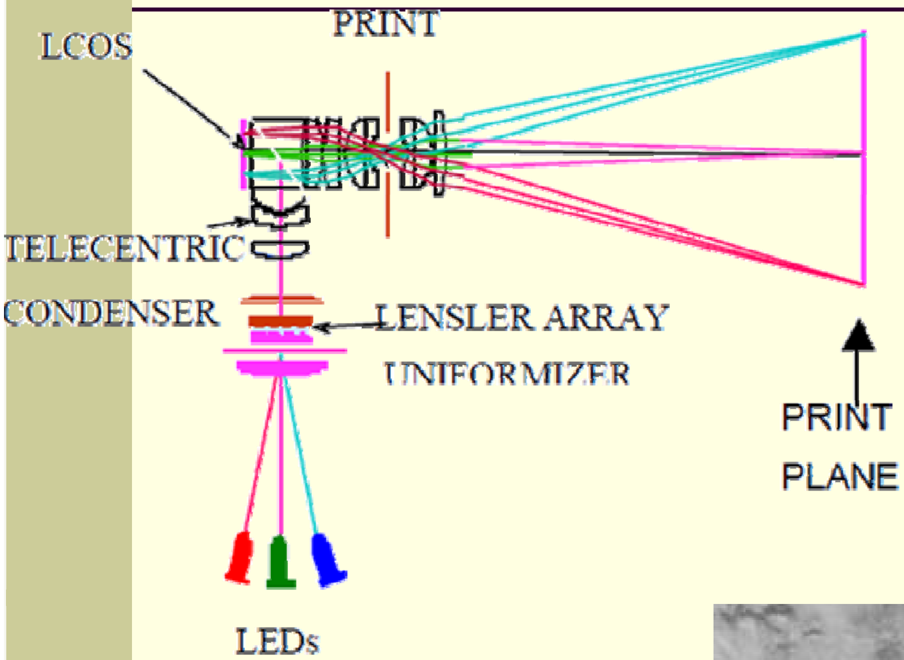
1mm thick crystal quartz will separate the ordinary and extraordinary spots by 6 microns at the sensor

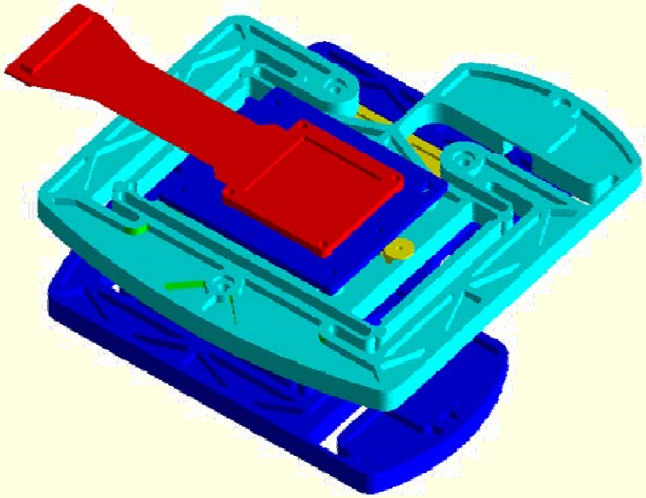


MTF curves for a blur filter vs. defocus



Anti aliasing solution: Mechanical dither in an LCOS printer





Obviously for dithering not to reduce resolution: the pixels have to be underfilled.

Solutions Kessl

Artifacts with Extended Depth of Focus (EDOF)

EDOF started with CDM (bought by Omnivision) , GG&C, DBLUR (an Israeli company) Xceed Imaging (Israel) and others.
Some smart phones are available with it (Nokia.)

The idea is to introduce to the design of a fixed focus lens a known phase mask and then capture the image with no focusing and retrieve the image using algorithms over a large depth of field.

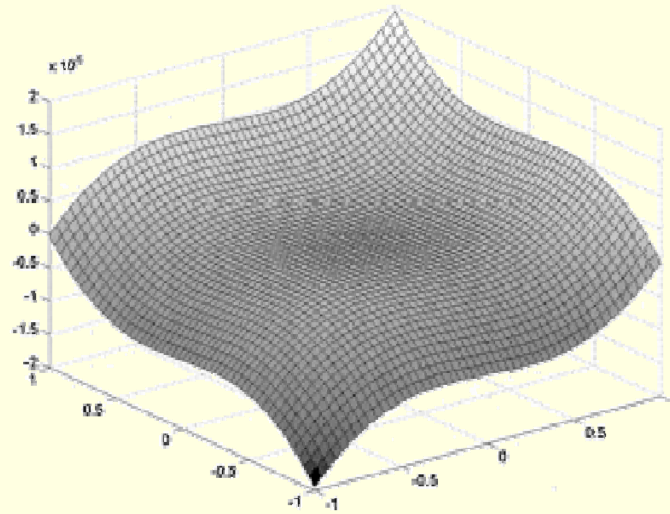
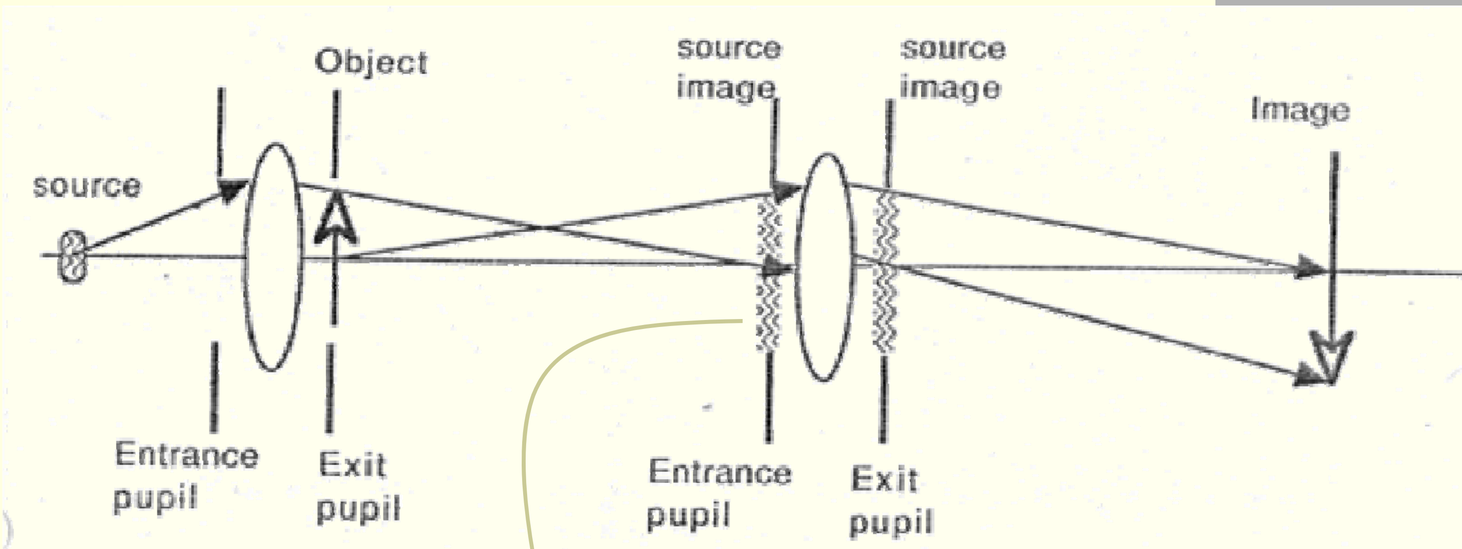


Fig. 2. Profile of a logarithmic phase plate.

EDOF cameras while greatly improved still have problems with some imaging situations especially in macro imaging ,lower light level imaging and text imaging (fringing) as compared with cameras using autofocus.

Good review: EDoF versus Auto-focus: Understanding the compromises involved
Published by Steve Litchfield at 20:12 UTC, April 17th 2011

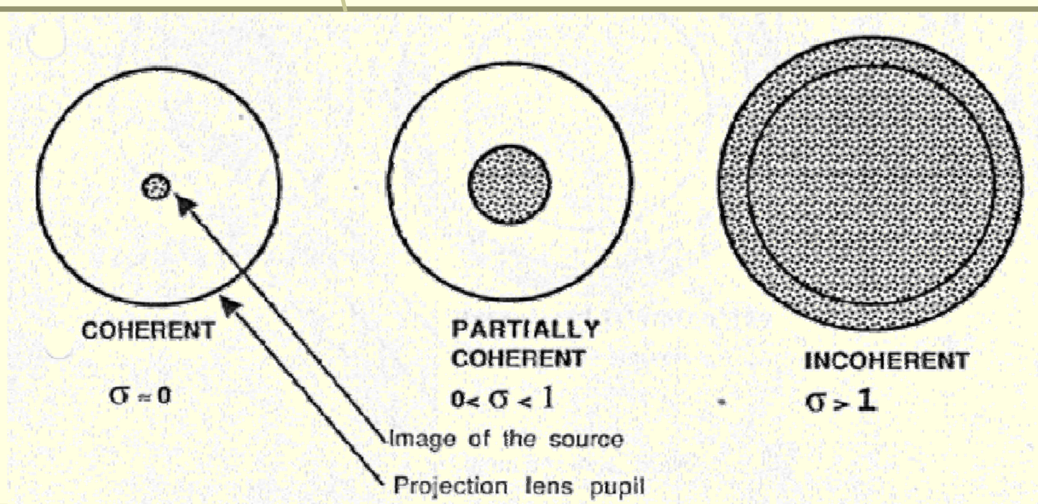
Schlieren systems in partially coherent illumination



Condenser / illumination system

Projection /imaging lens

Degree of coherence



Schlieren systems and phase objects

- Schlieren systems are systems which convert object phase to intensity such as Zernike microscopes or the TI DLP projector
- When the object phase is unwanted- it creates an artifact which needs to be suppressed
  - Examples: cover glass imperfections on LCOS image sources or on CCD/CMOS sensors
  - Anti friction structures on motion picture films
  - Related to the traditional term: “scratch and dig”.

Suppression of Schlieren artifacts: DataCine – a HD telecine

Object phase suppressed with an integrating cylinder producing incoherent line illumination

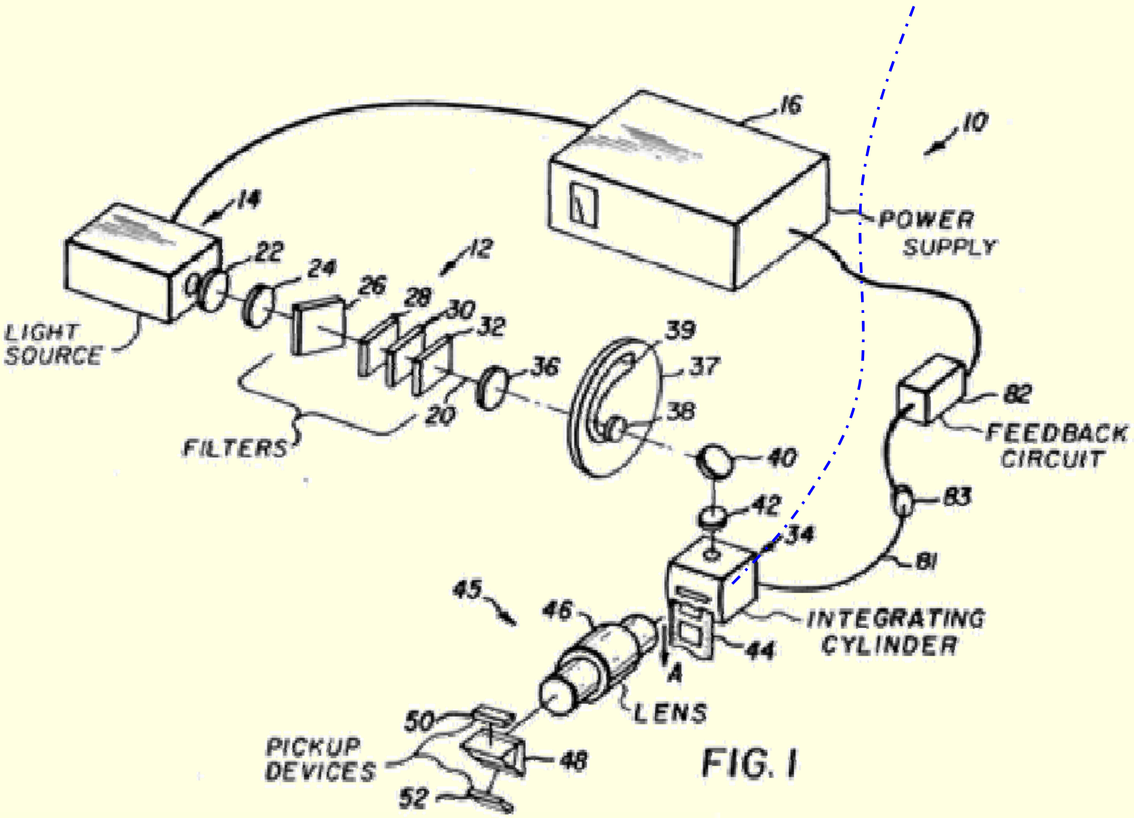


FIG. I

“Dirty windshield” artifact

Sunlight scattered off structures and discontinuities on the windshield

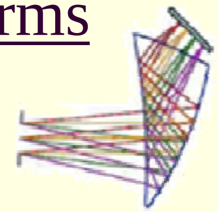
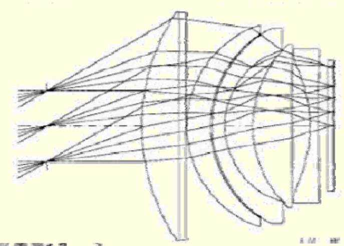
This artifact is present in a number of systems with or without windshields.

Near to Eye display:
What does everyone want?

Oakley Thump = Sunglasses+MP3

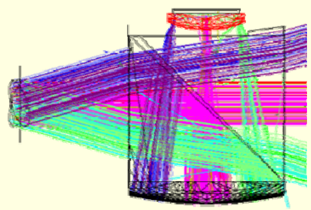
"Oakley look" .	i.e., thin & small optics
Augmented imaging	preferably an optical see-through channel
Low cost	& small image generators (OLED, LCOS, …)
Wide field of view	30^0 deg to 110^0 full diagonal field
Large eye box	>10 mm ,for eye ball movement + loose alignment
Large eye relief	> 20 mm, for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

NEDs: categories of optical design forms

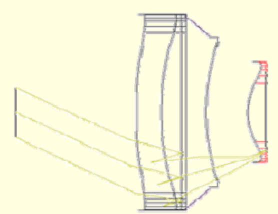



- Magnifiers i.e. eye piece + image generator

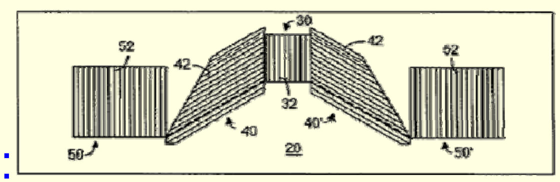
- Relay based NEDs
- “Bird’s bath designs”




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



- Pupil splitting :
- Segmented (or tiled) NEDs:

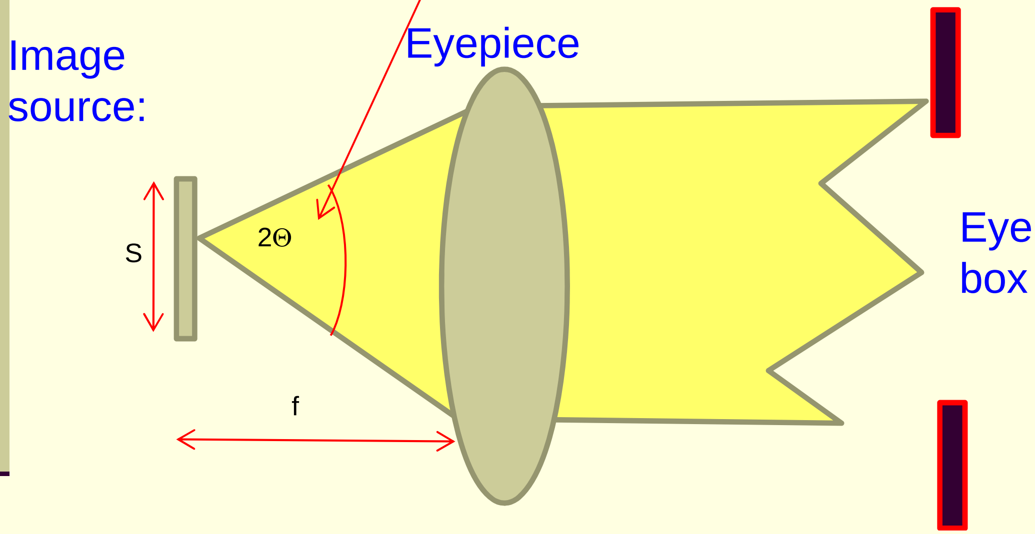


- Other: Foveated; Fiber scanning; Retina scanners; etc.

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

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

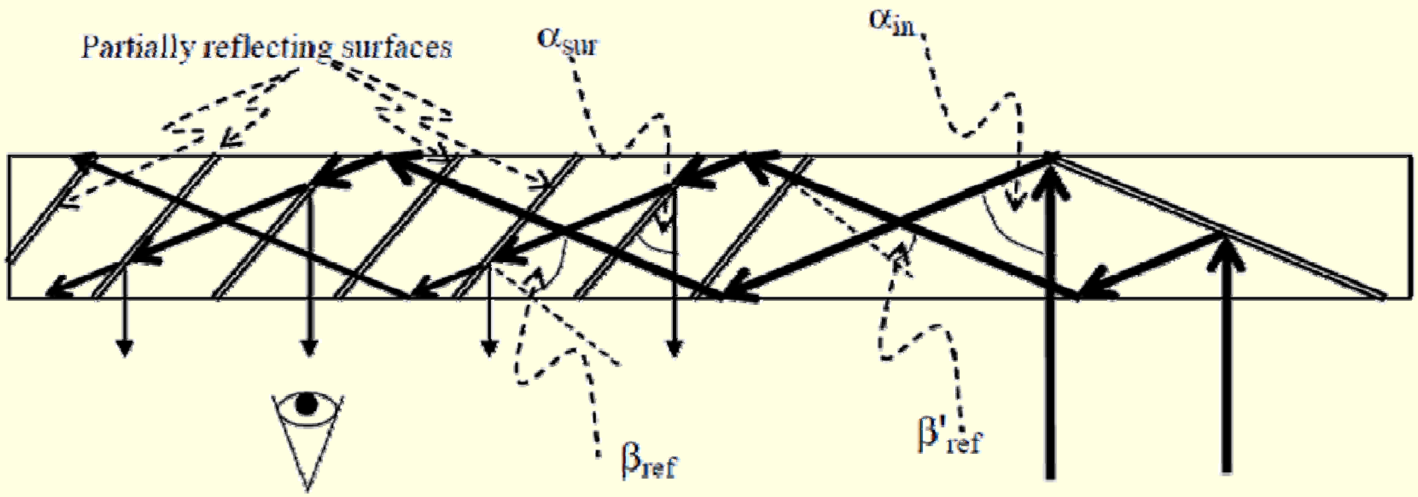
* Low F/number (= high Numerical Aperture) for efficiency
* large eye box
* Short focal length for large field and small optics

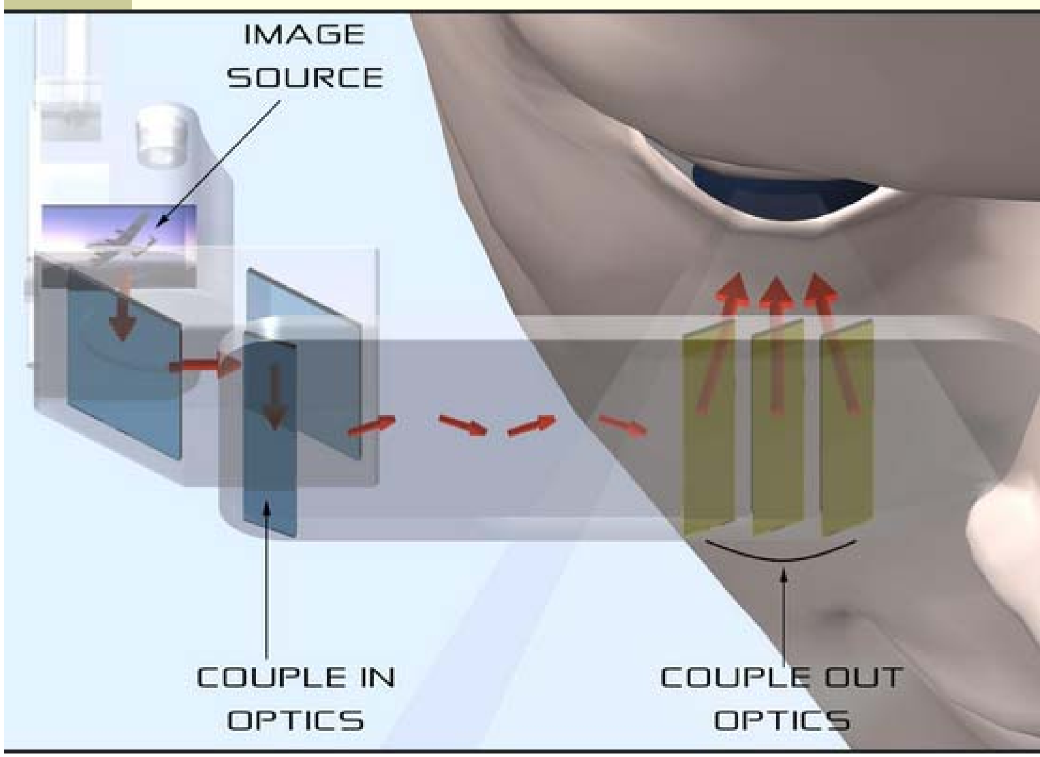


$NA = \sin(\theta)$
(Eye Box) = 2*f * NA
FOV = S / f

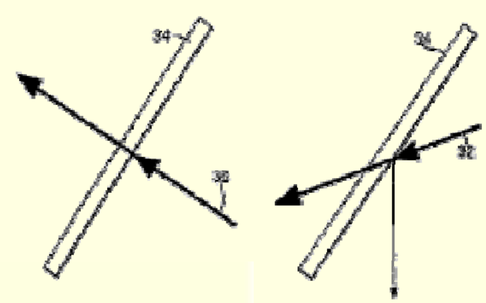
However , short focal length means small eye box, so we use a short focal length and get a small exit pupil and then expand it by replication to fill the eye box.

LUMUS one dimensional Light-guide Optical Element (LOE)





inventor: Yacov Amitai



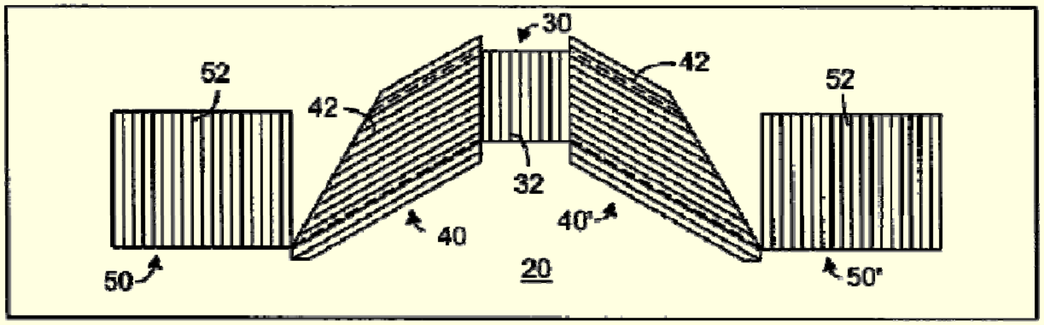
nics Solutions, Ltd.
www.kessleroptics.com

The Nokia technology

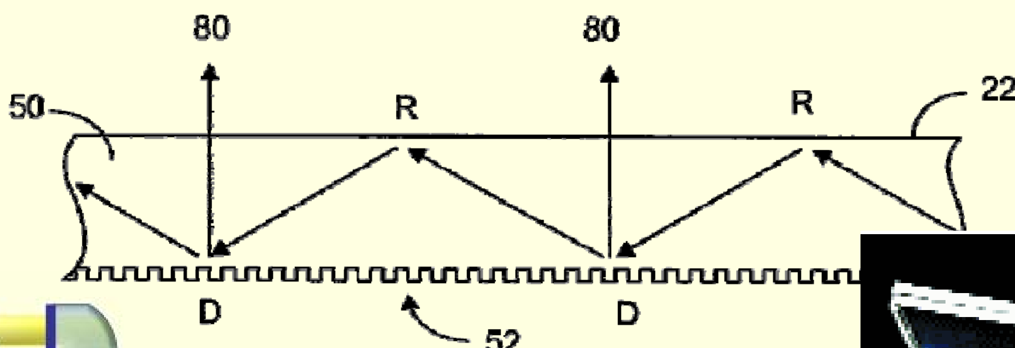
(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2006/0126182 A1**
Levola (43) **Pub. Date: Jun. 15, 2006**

(54) GENERAL DIFFRACTIVE OPTICS METHOD FOR EXPANDING AN EXIT PUPIL

Publication Classification



Problem: limited FOV since this is basically a Bragg reflector obeying the Bragg condition



Segmented or tiled NEDs

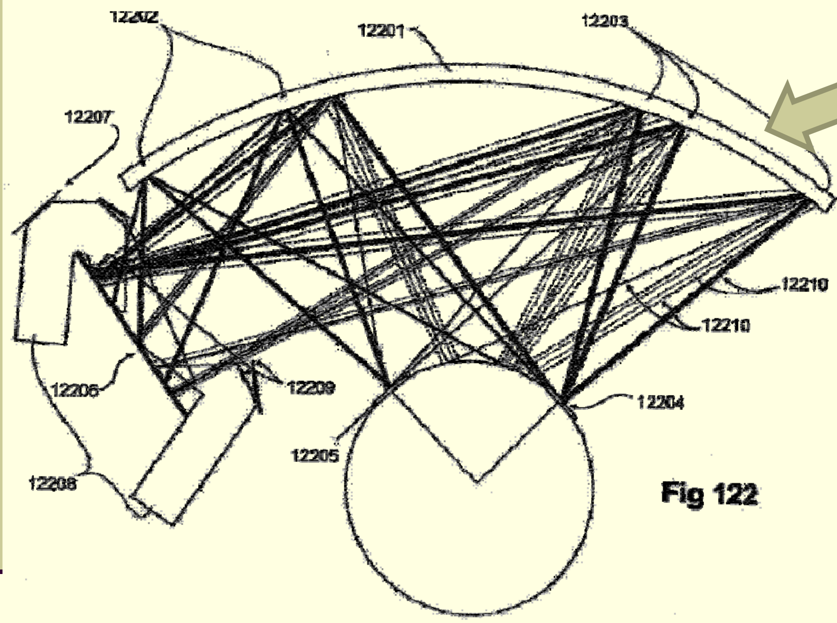


Fig 122

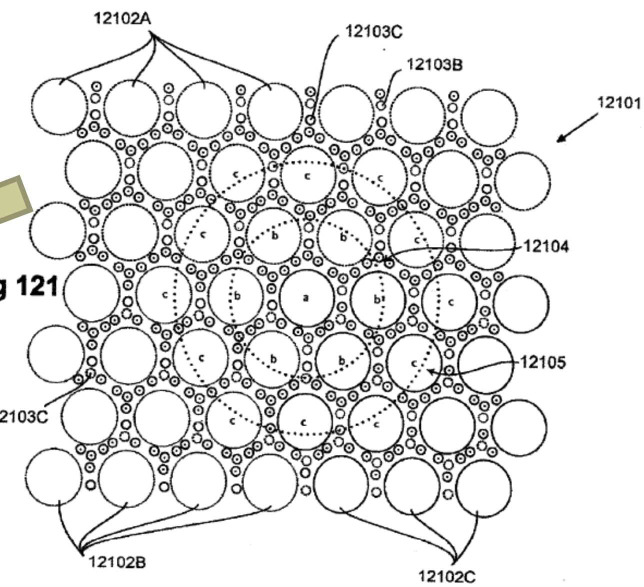


Fig 121

Patches of different size holograms dispersed over the combiner and interact with an array of laser beams.

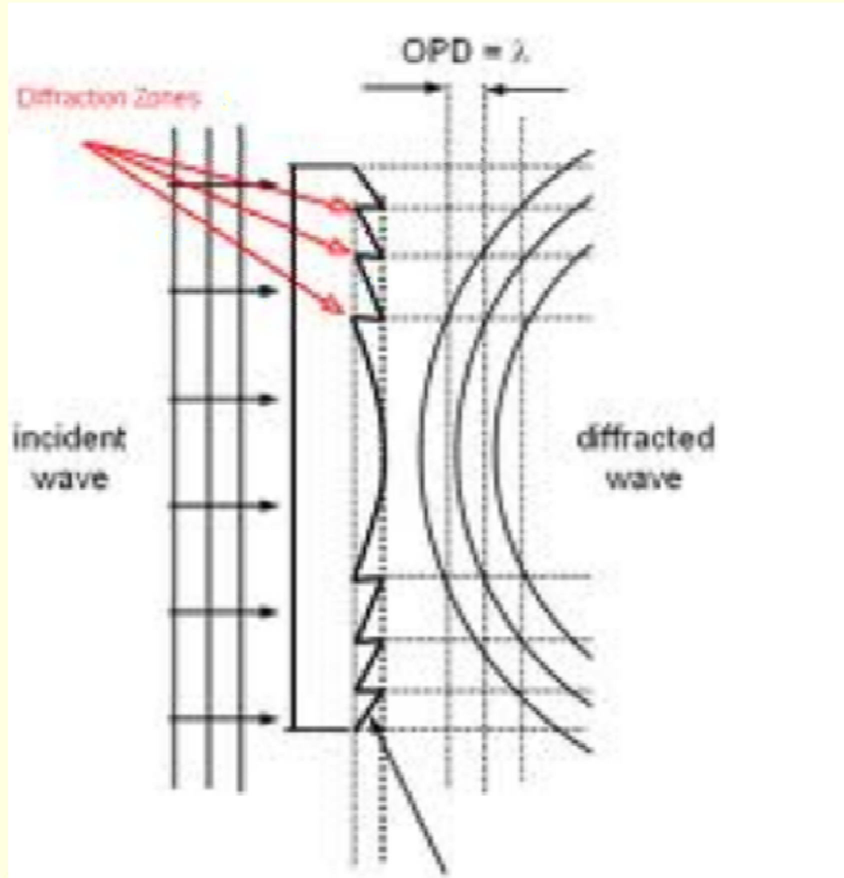
High potential for sunlight "dirty window" scattering

Chaum et.al
US20120/0149073A
100 pages, 300 figures,
85 claims

Dirty windshield artifact : in cameras

Scattering from diffractive optics elements (DOEs)
(see Bob Fisher HNDBK of Optical Systems Design- the bloopers and blunders in optics section)

KODAK story of the DOE white and magenta flare. The optical designers incorporated a 1.6 mm baffle to kill the scattered sun light but this was removed by the camera designers for esthetic reasons. The production was cancelled.



The message": beware of scattering from any discontinuities in the pupil.

Shimmering /swimming

<u>The artifact:</u>

The field of view seems to be swimming when the head or eye are moving within the system eye box. Also: convergence is affected and thus 3D perception

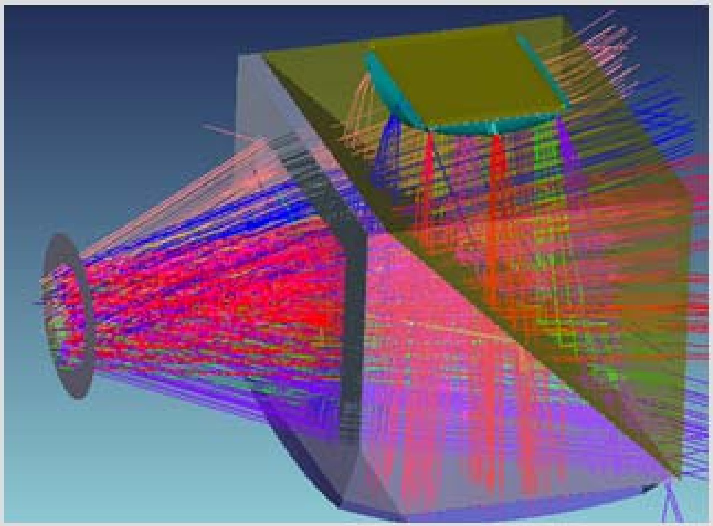
<u>Can be found in:</u>

- In Near to Eye Displays
- Biocular systems
- Binocular systems
- Any system with eyepieces with large entrance pupils (eye boxes) within which the eye can move about.

Correcting for shimmering

See-through: SXGA; 50 degrees diagonal; 10 mm Eye Box ;23mm Eye Relief; 0.78" OLED

Kessler and Bablani , USA 8094377



Two ways to design for low shimmering system:

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.

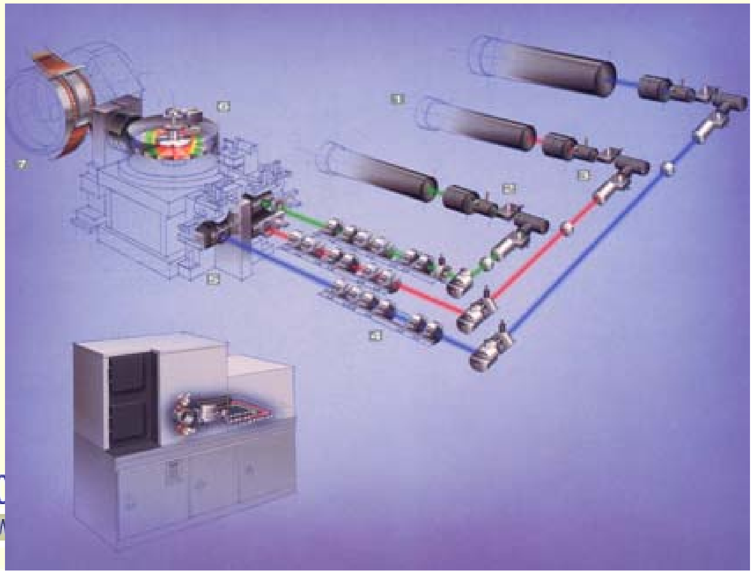
Beams registration in RGB laser systems

Similar to the lateral color aberration but the source is laser pointing errors

The solution is to design the laser channels so pointing is minimized. This is done by designing the laser trains and handle simultaneously

1. the Gaussian beam properties of the beams- mainly waist size and location
2. The geometrical properties of the system so the planes of minimum deviation are optical conjugated to the image plane.

For this, there is design method called the YY diagram.



$y\bar{y}$ Diagram, a powerful optical design method for laser systems

David Kessler and Roland V. Shack

We present a new method for synthesizing and analyzing laser systems based on the use of the $y\bar{y}$ diagram. The diagram is commonly used to represent two rays, the marginal and the chief rays, as they propagate through an optical system. Since a Gaussian beam can be represented by two rays, it is possible to use the $y\bar{y}$ diagram to represent these rays. This results in a representation of the beam as a single ray line on the $y\bar{y}$ diagram with simple graphic interpretations for the beam parameters. An equivalent representation of the Gaussian beam on the $u\bar{u}$ diagram is also presented and discussed. Complex design problems may be reduced to simple graphic problems, which often lead directly to algebraic solutions. Examples of $y\bar{y}$ diagrams are given for beam transfer through simple optical systems, including gradient optics. Diagram transformations are discussed and design examples are given of a three-element afocal system and a three-element collimator.

Key words: $y\bar{y}$ Diagram, laser beam, Gaussian beam, optical design, Delano diagram.

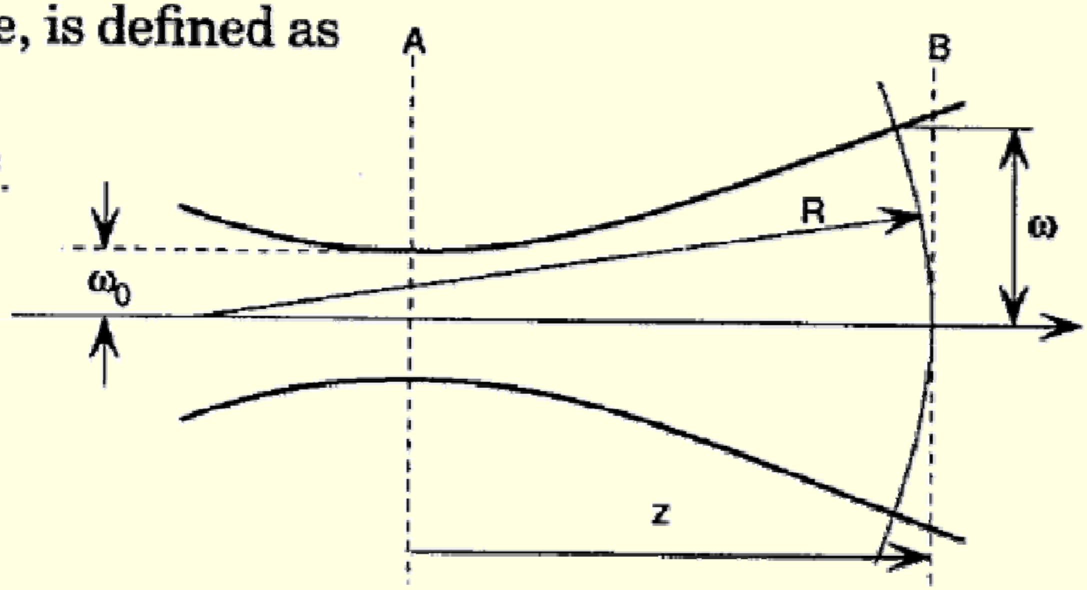
APPLIED OPTICS / Vol. 31, No. 15 / 20 May 1992

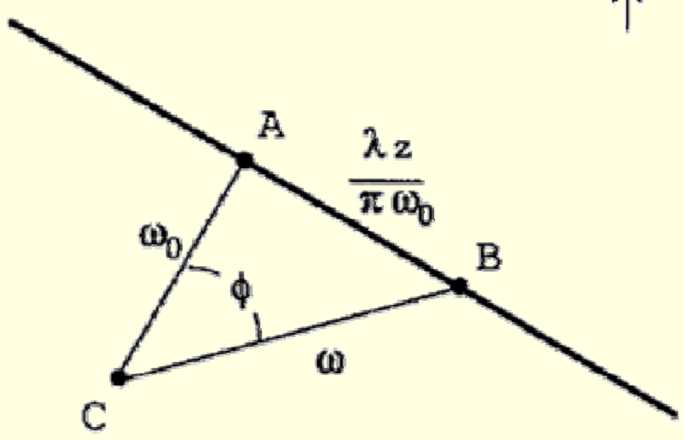
Representation of a laser Gaussian beam by a line and a point

$$\omega^2 = \omega_0^2 + \left(\frac{\lambda z}{\pi\omega_0}\right)^2 = \omega_0^2\left[1 + \left(\frac{z}{z_0}\right)^2\right],$$

where z_0, the Rayleigh distance, is defined as

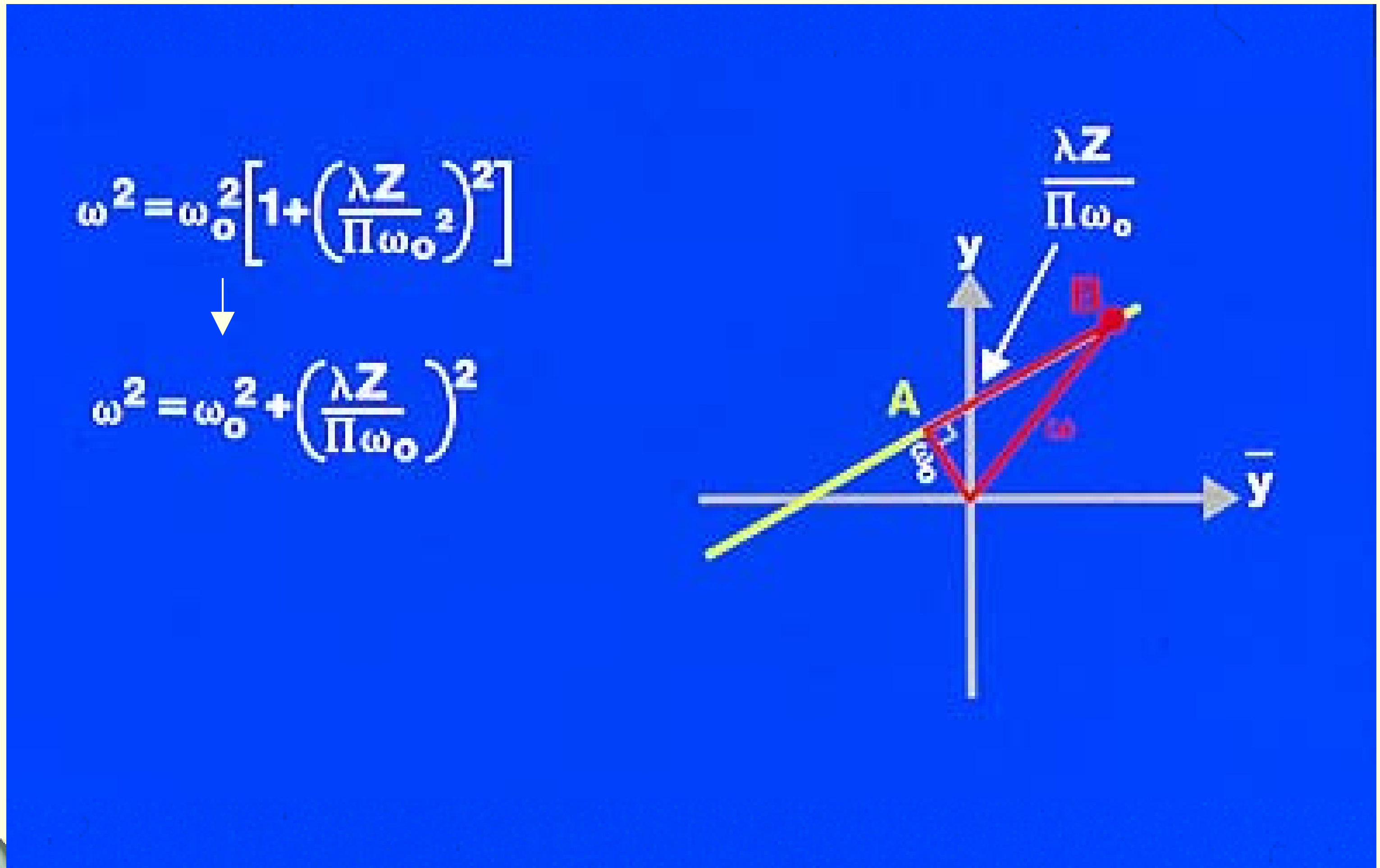
$$z_0 = \frac{\pi}{\lambda}\omega_0^2.$$



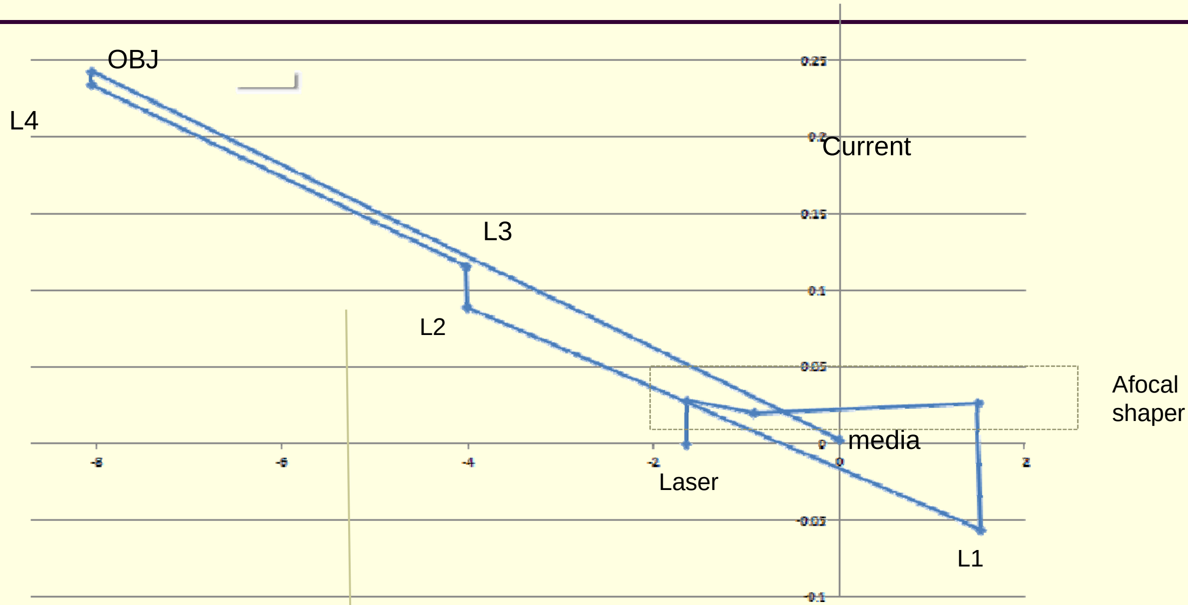


Representation of a Gaussian beam by a line and a point.

Beam parameters on the Y-Ybar diagram



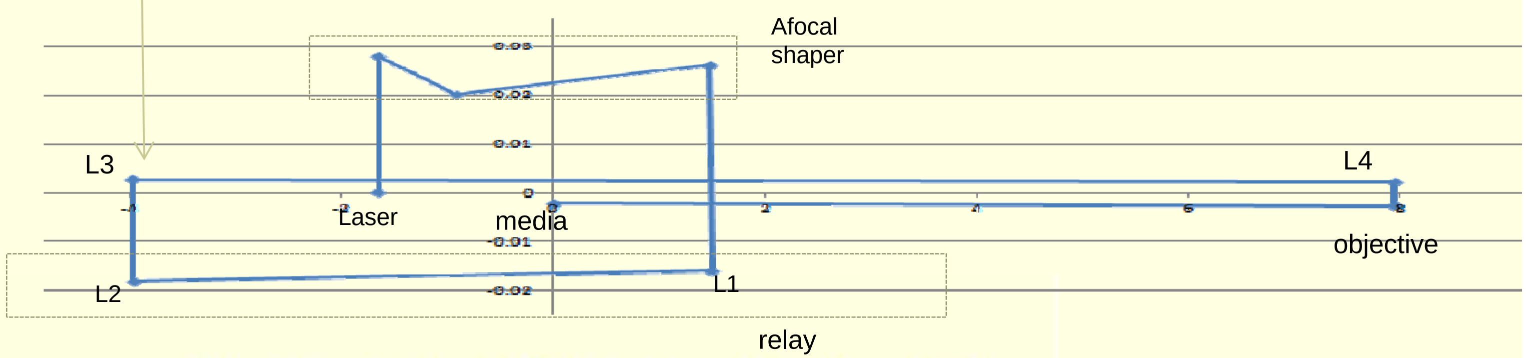
Example: Laser marking system: YY diagrams before and after



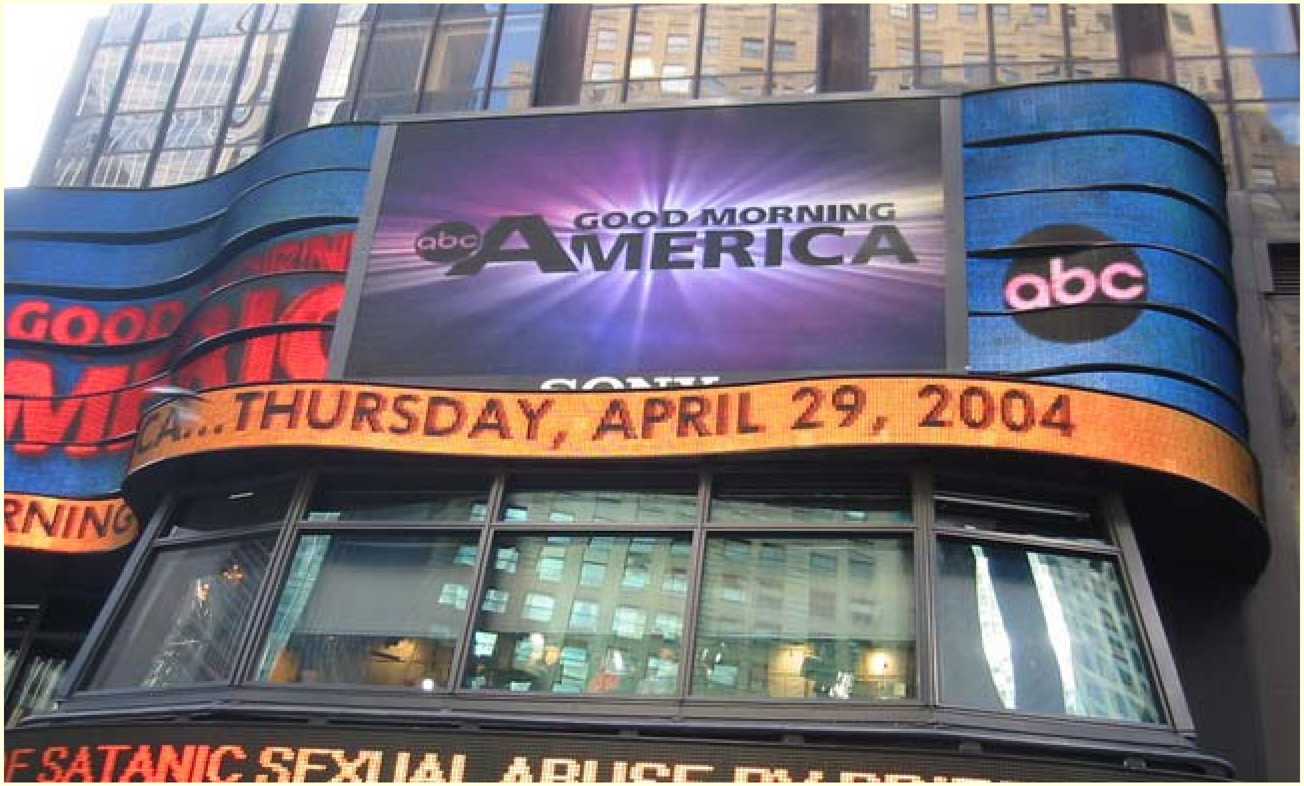
There is a small , non zero waist size at the media

?

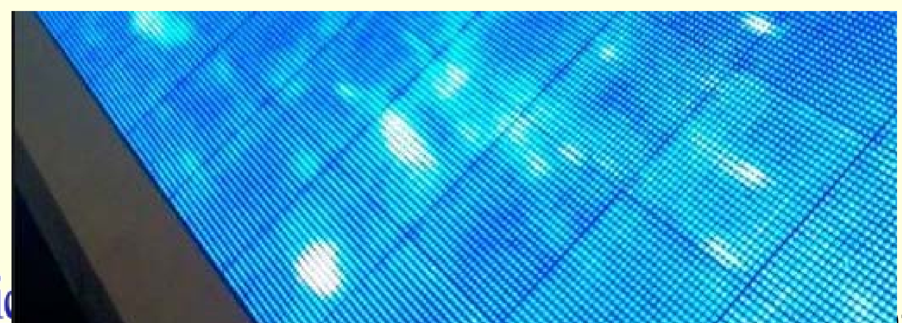
YY diagram for modified system



Tiling artifacts



LED displays are usually assembled of 6” x 6“ modules



MODULATOR–INDUCED STREAKING ARTIFACT IN LASER FILM PRINTER IMAGES

Kwok–leung Yip, David Kessler, and Scott J. Daly*

Health Sciences Research Laboratories*,

SPIE Vol. 1254 Optical Hard Copy and Printing Systems (1990) / 33

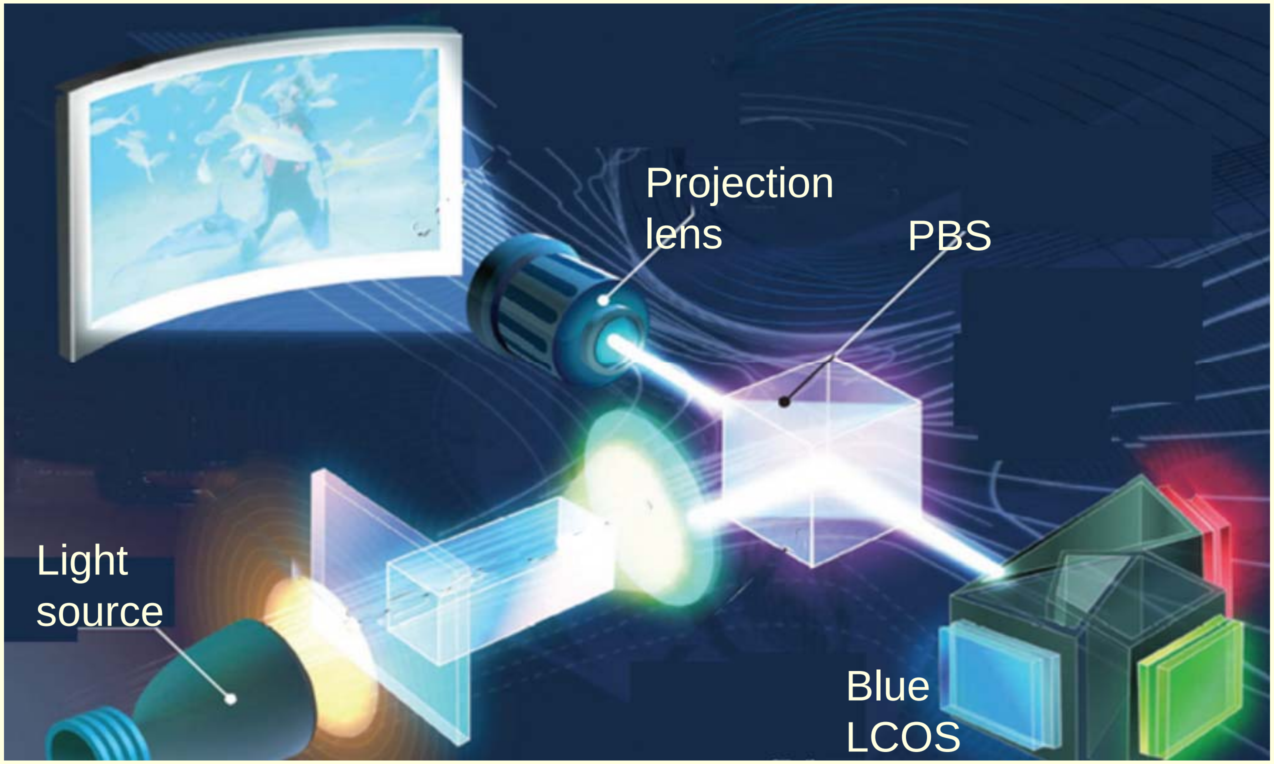
- The Just Noticeable Difference (JND) for streaking is ~ 0 .1%

- Holds for long streaks even when bellow the resolution of the eye of about 1’.
- (this is why we see the high tension wires from the airplane)

- Tiling is doable spatially in projectors for example on screen with gain factor of 1 (i.e. Lambertian screen) using matching and blending algorithms.

- **Tiling in both the spatial and the angular domains is difficult.** This is why in Times Square we see the 6x6” LED modules when looking at the display off axis)

Polarization artifacts-stress birefringence



Birefringence in the PBS and beam combiner and field lenses are indistinguishable from the LCOS image information.

The first LCOS theatre cinema projector.

Thermal stress birefringence is the central issue of such a design

The design has to consider special glasses with low stress birefringence but unfortunately are also the glasses laden with lead like SF57.

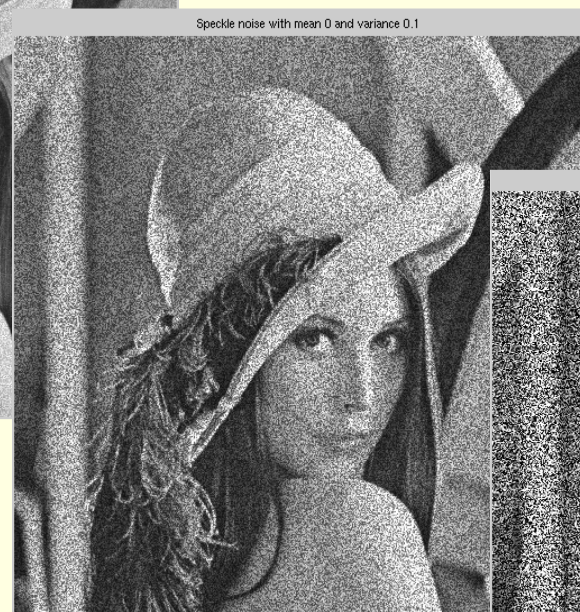
The Kodak Digital Cinema projector for Digital Cinema ~12,000 screen lumens, ~2,000:1 contrast ratio

SPECKLE

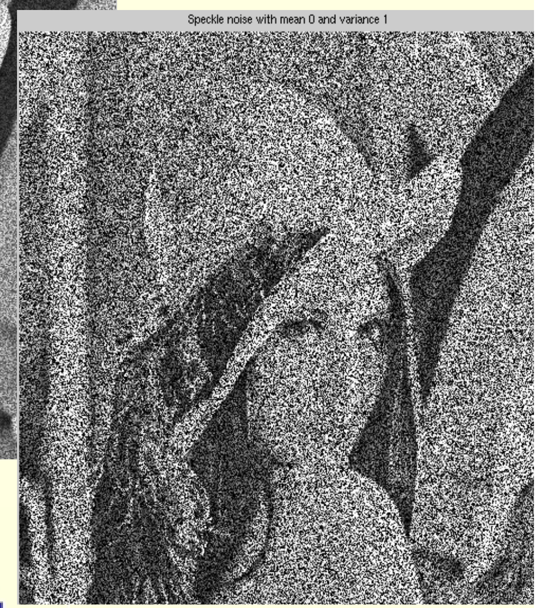
C=0.0

C=0.04

C=0.5



C=0.84



C IS THE SPECKLE CONTRAST

SPECKLE reduction techniques

Joseph Goodman in the book “Speckle Phenomena in Optics, Theory and Application” (Roberts and Company Publishers, Greenwood Village, Colo., 2007).

1. Introduce polarization diversity;
2. Introduce a moving screen;
3. Introduce a specially designed screen that minimizes the generation of speckle;
4. For each color, broaden the spectrum of the sources or use multiple lasers at slightly different frequencies, thereby achieving wavelength diversity in the illumination;
5. For each color, use multiple independent lasers separated spatially, thereby achieving angle diversity in the illumination;
6. Overdesign the projection optics as compared with the resolution of the eye;
7. Image a changing diffuser with random phase cells onto the screen; and
8. Image a changing diffuser with deterministic or orthogonal phase codes onto the screen.

Bottom line: to reduce the speckle – make the lasers look more like an incoherent lamp and

United States Patent

Silverstein et al.

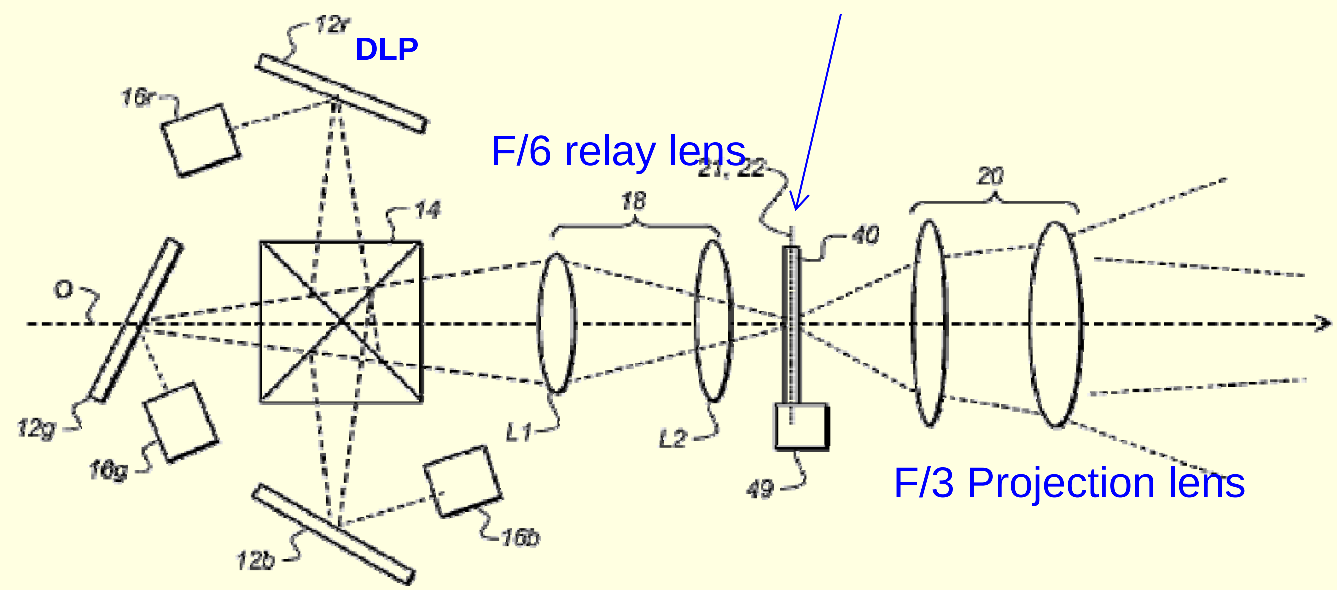
(10) **Patent No.:** **US 8,172,403 B2**

(45) **Date of Patent:** ***May 8, 2012**

PROJECTION WITH CURVED SPECKLE REDUCTION ELEMENT SURFACE

Inventors: **Barry D. Silverstein**, Rochester, NY (US); **Joseph R. Bietry**, Rochester, NY (US); **Gary E. Nothhard**, Hilton, NY (US); **Robert Metzger**, Fairport, NY (US); **Andrew F. Kurtz**, Macedon, NY

Intermediate image with a dynamic speckling reducing element



Electronic vs. optical correction

Image algorithms people have sometimes the tendency to apply them universally.

Some artifacts should be left for the optics to correct:

- Aliasing
- Focusing
- Schlieren artifacts
- Banding
- Ghost images
- Speckle

Some artifacts can be corrected well by electronics/processing

- Distortion
- Lateral color
- $(\text{Cosine})^4$ falloff

Lateral Color: optical vs. electronic correction

Uncorrected lens with a focal length f has a longitudinal color of

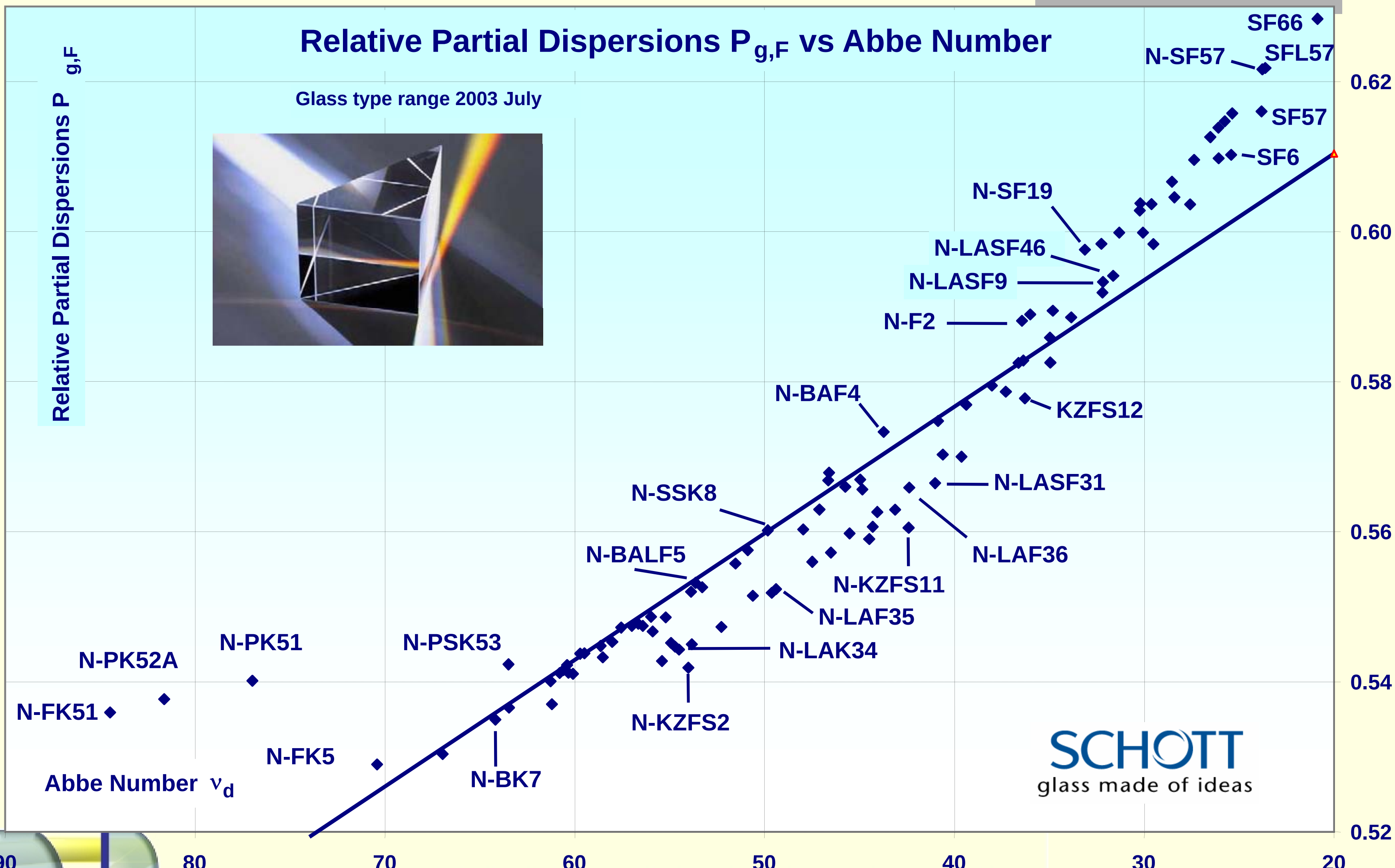
$$\frac{df}{f} = \frac{1}{\nu}$$

Where ν is the Abbe number which is between 30 for flit glasses to 80 for crown glasses. After achromatization the achromat will have typically:

$$\frac{df}{f} \sim \frac{1}{1800}$$

Beyond that , for apochromats, special glasses are needed and other issues need to be considered such as color variations of the aberrations especially sphero-chromatism.

Relative Partial Dispersions $P_{g,F}$ Vs. Abbe Number



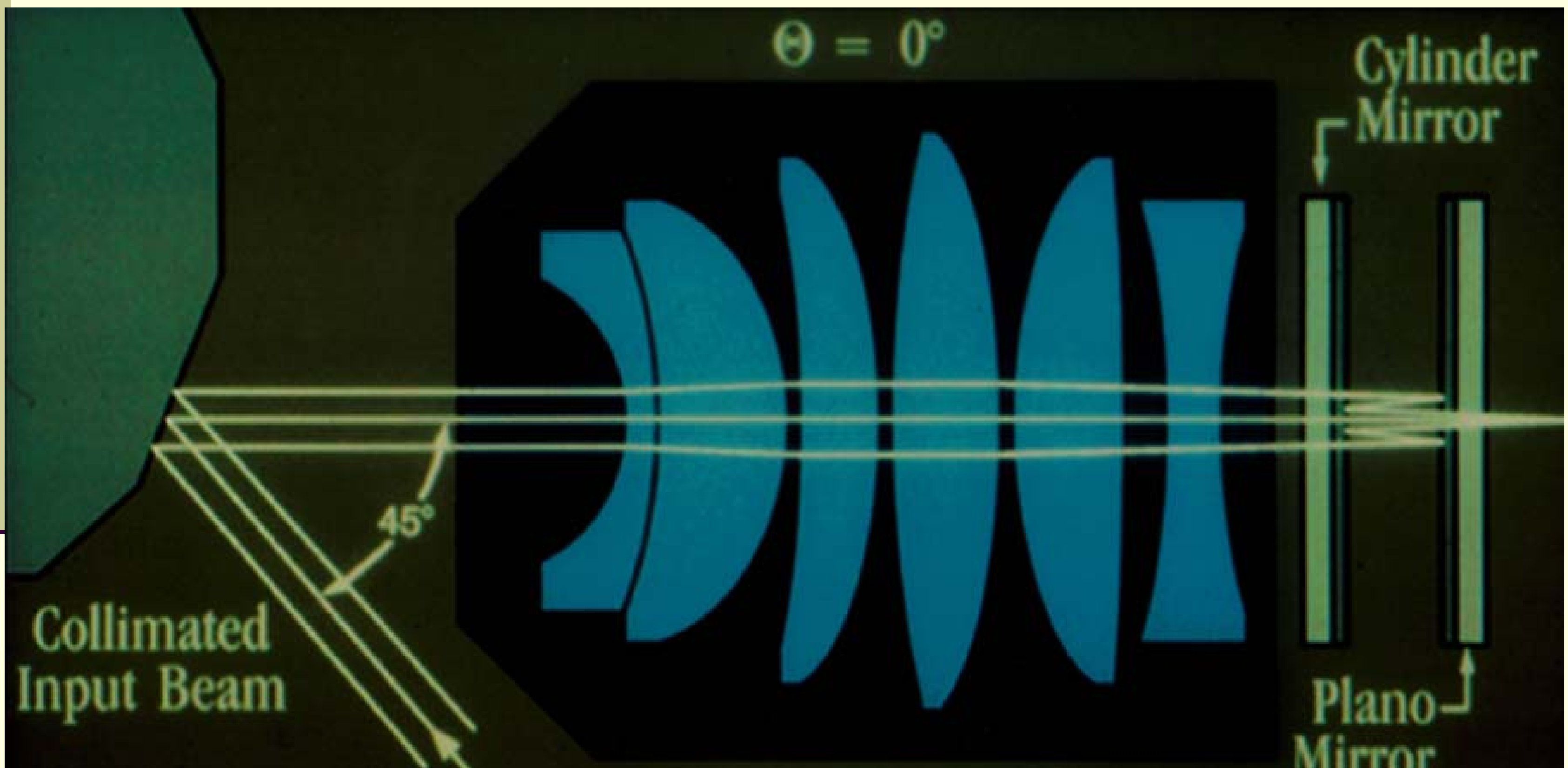
Example: **lateral color** in RGB laser projection or printing

Achromatic scan lenses or projection lenses can be readily designed to correct down to 2 or 3 pixels. Further reduction to ½ or ¼ pixel : “secondary color” correction with special glasses needed.

Electronic correction is extremely beneficial in bringing the correction down to half or a quarter of a pixel.

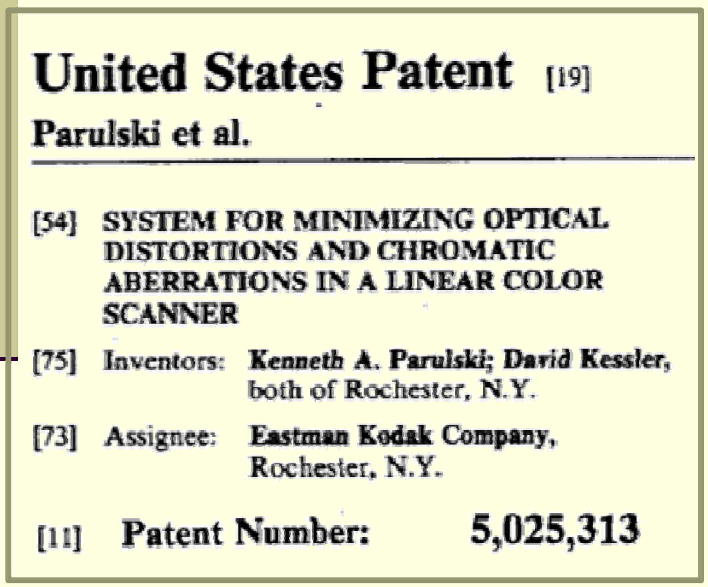
f-θ scan lens for motion pictures printer .

Achromatic design & “electronic secondary color” correction AND optical polygon pyramid correction



Electronic secondary color correction

- Lateral color is basically change of magnification with color
- Processing thus can be used also in cameras and CCD/CMOS scanners


United States Patent [19]

Parulski et al.

[54] SYSTEM FOR MINIMIZING OPTICAL DISTORTIONS AND CHROMATIC ABERRATIONS IN A LINEAR COLOR SCANNER

[75] Inventors: Kenneth A. Parulski; David Kessler, both of Rochester, N.Y.

[73] Assignee: Eastman Kodak Company, Rochester, N.Y.

[11] Patent Number: 5,025,313

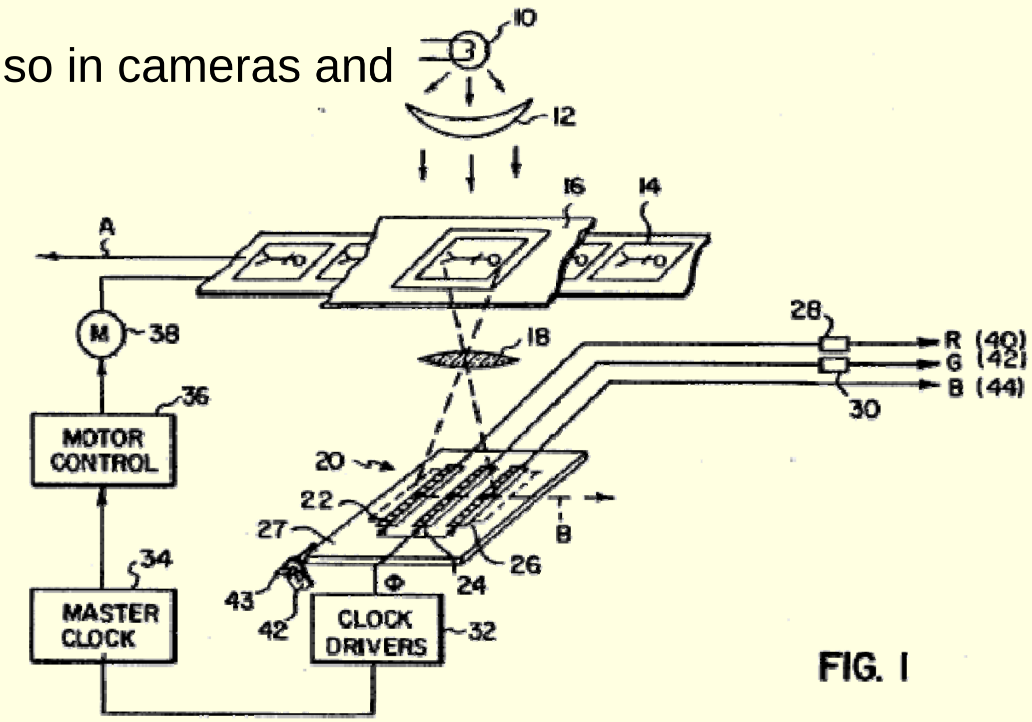
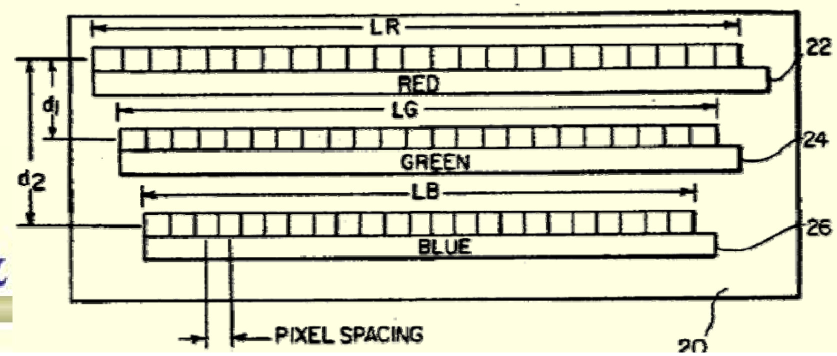
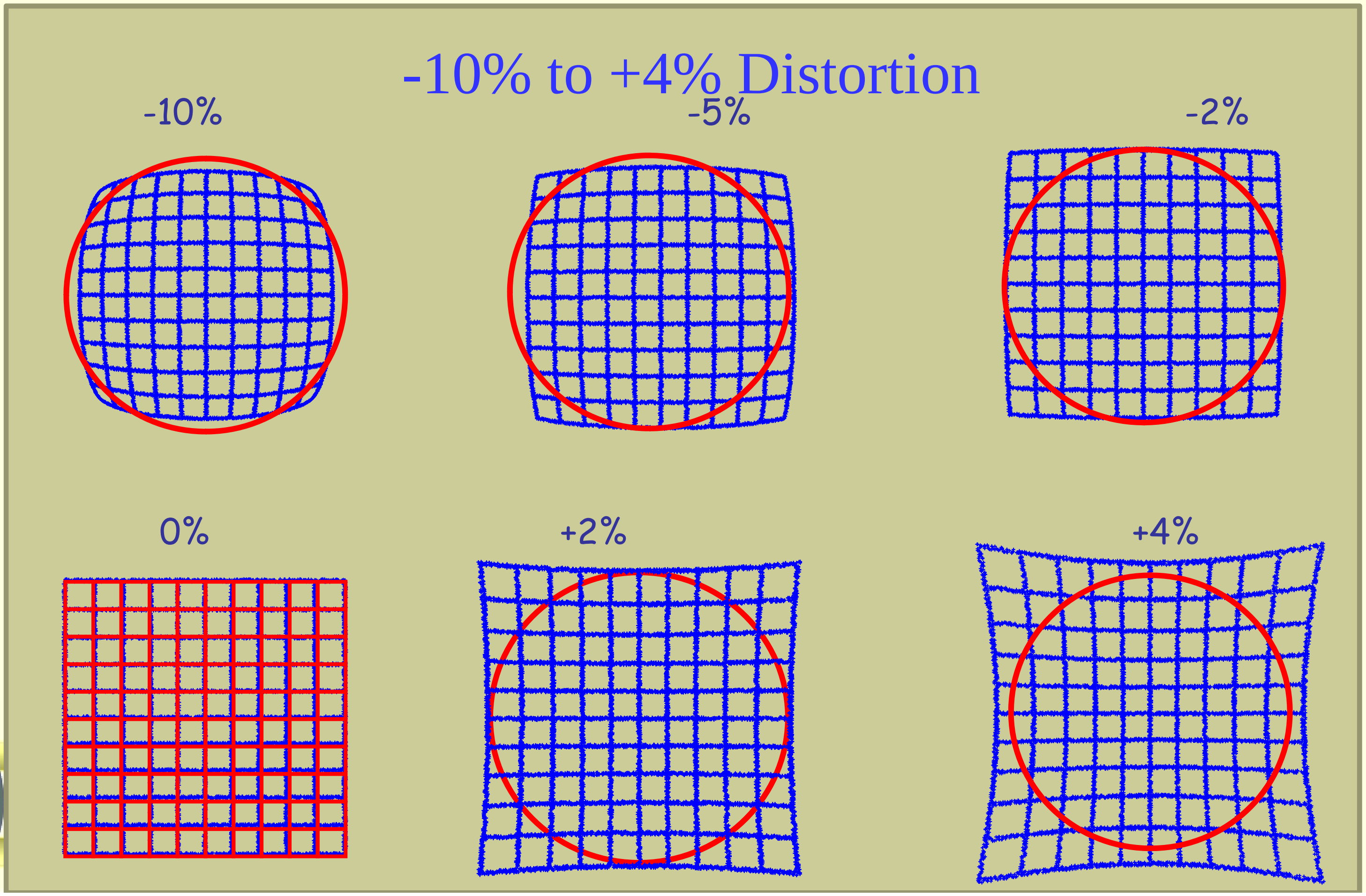


FIG. I



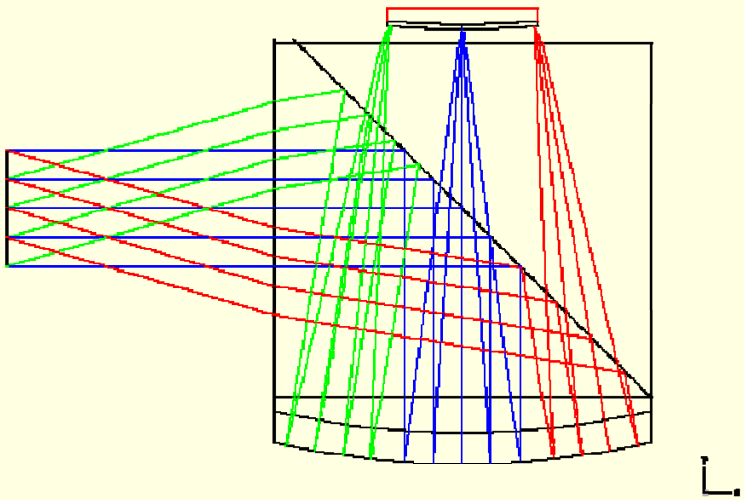
Distortion

Electronic correction at this range of distortion values is beneficial. Beyond it, loss of pixels is an issue

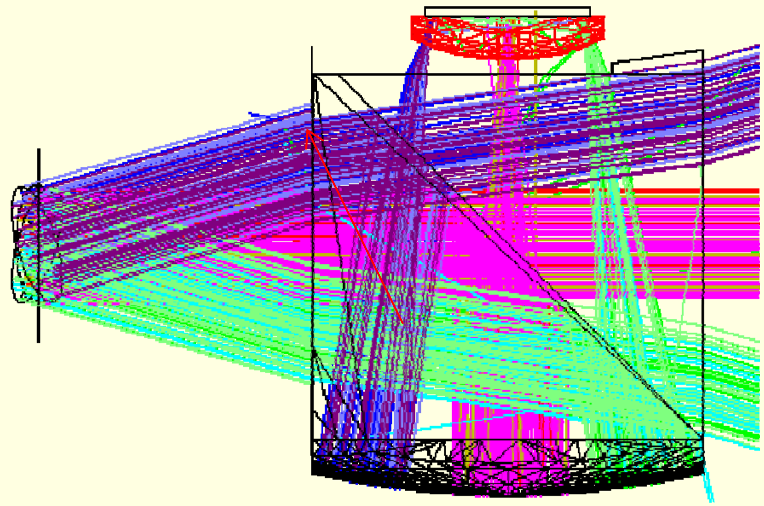


Artifacts ,Non Sequential & sequential modeling

<u>Sequential modeling:</u>
System described in terms of
- Fields
- Numerical aperture or aperture size
- Spot diagrams



<u>Non Sequential modeling:</u>
System described in terms of
- Sources dimensions
- sources divergences
- Irradiance on detectors



Fast optimization
Wavefront analysis and diffraction & MTFs
Tolerances, plate and index fitting…..
Merit function construction should include artifacts

Solid modeling
Ghost analysis
Scattering/glare from optical & mechanical components

Summary

• Artifacts are important and should be considered from the start in the design of imaging systems.

• A variety of artifacts in imaging systems and correction means encountered by the author and colleagues were discussed.

• The correction of artifacts should be mainly in the optical domain

• “Curb your enthusiasm” for correction by algorithms or electronic means. Electronic and processing correction methods should be used “mildly” and mostly for chief ray corrections (lateral color and distortion).

•Thank you for the invite and for your attention