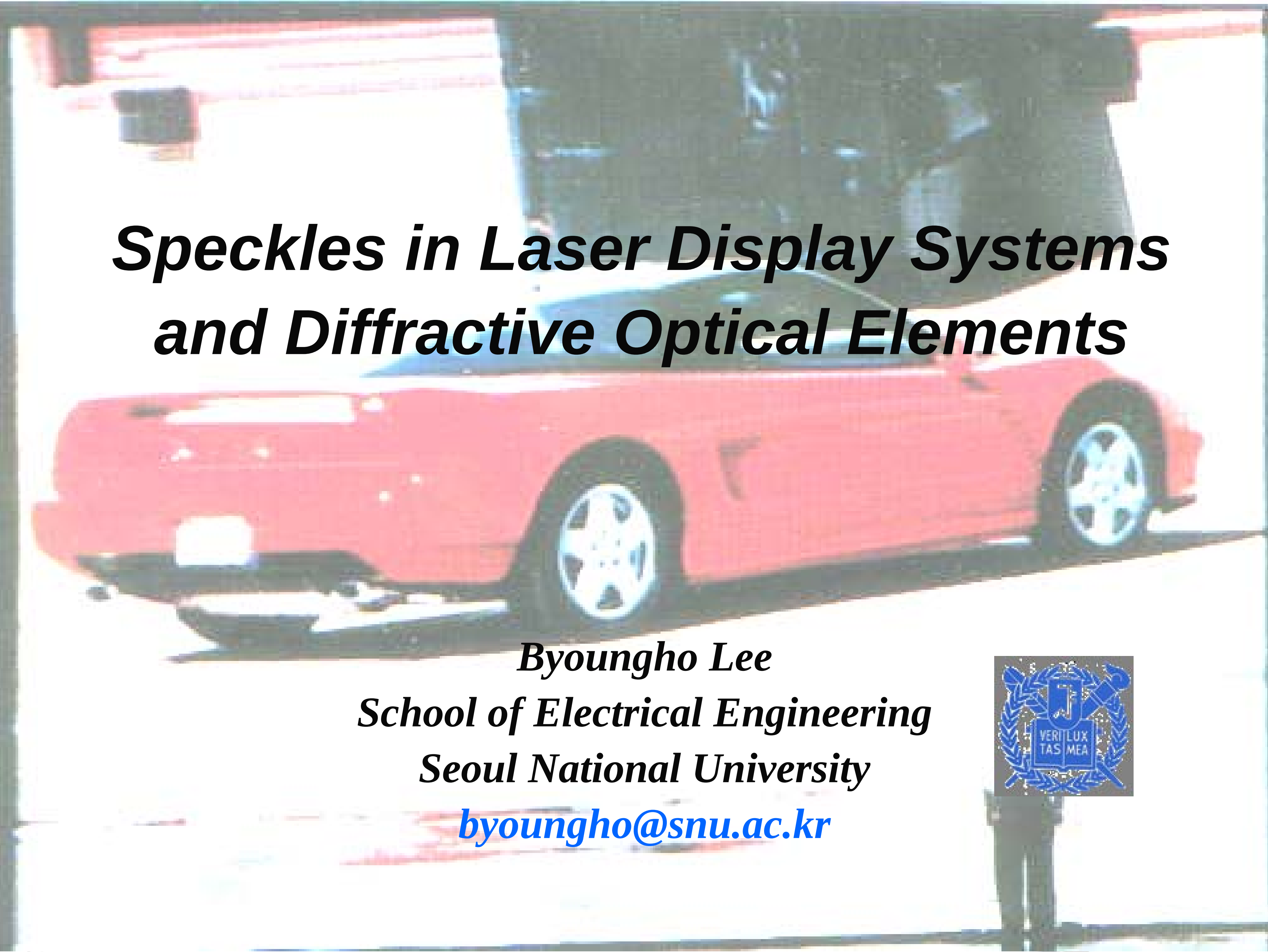


Speckles in Laser Display Systems and Diffractive Optical Elements

Byoungho Lee

School of Electrical Engineering

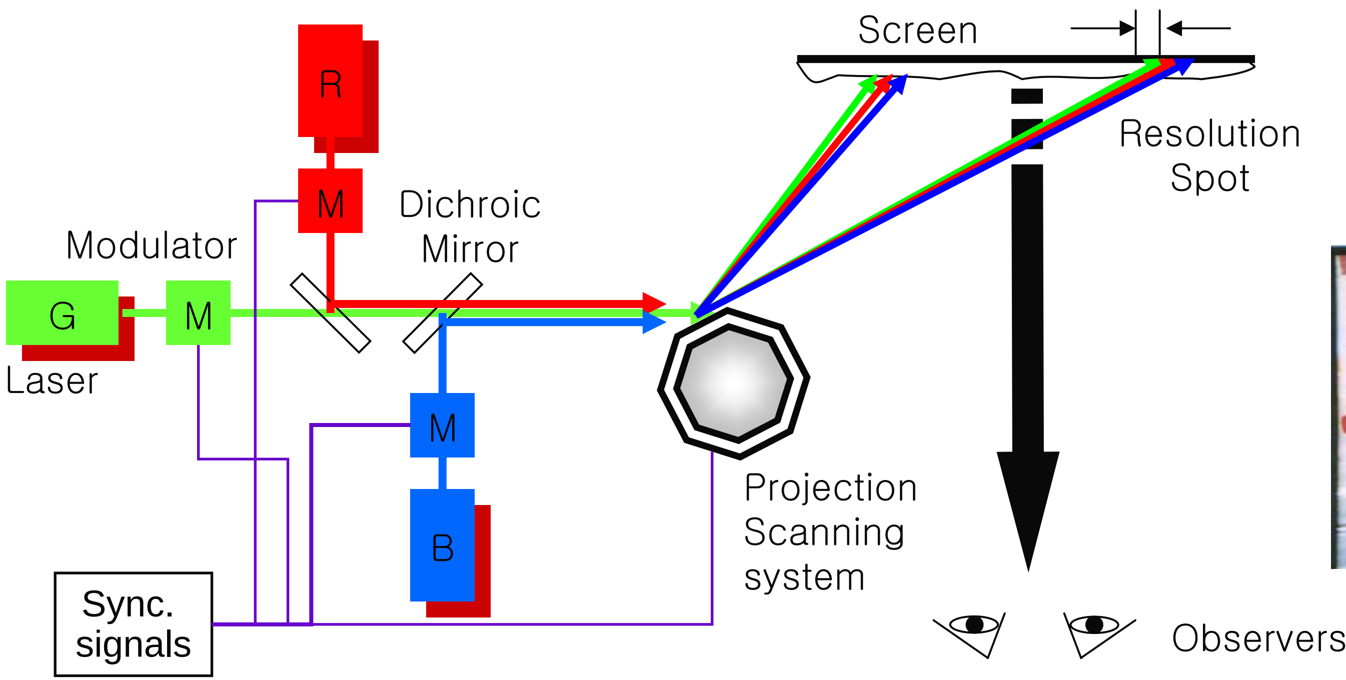
Seoul National University

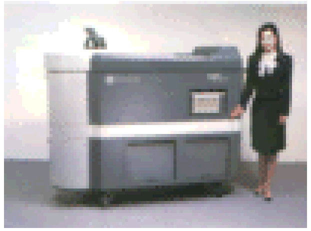
byoungho@snu.ac.kr

Contents

❑ Laser display system (scanning)

✓ RGB lasers, modulators, mirror/grating scanning devices, and display screen

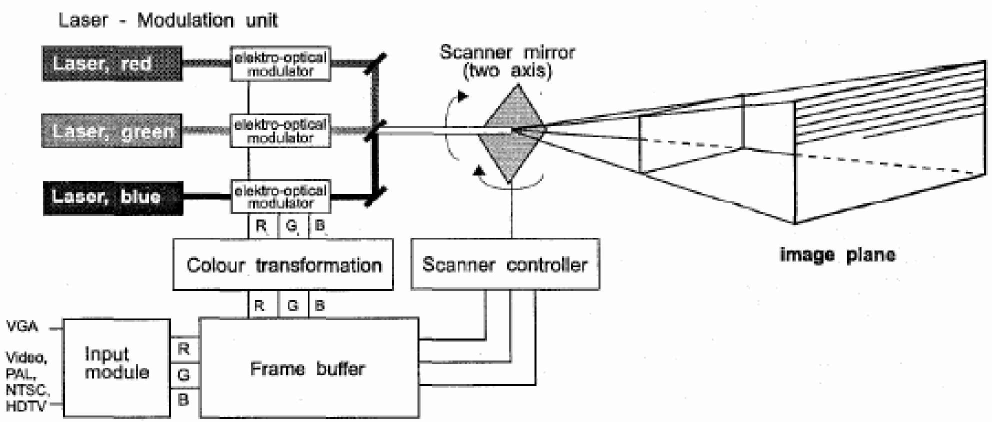


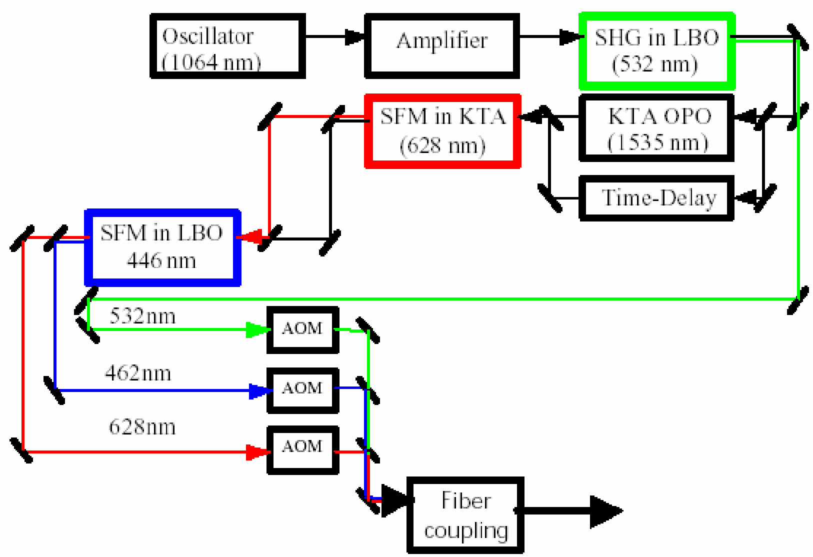


Schematic diagram of a laser display system using scanning optics

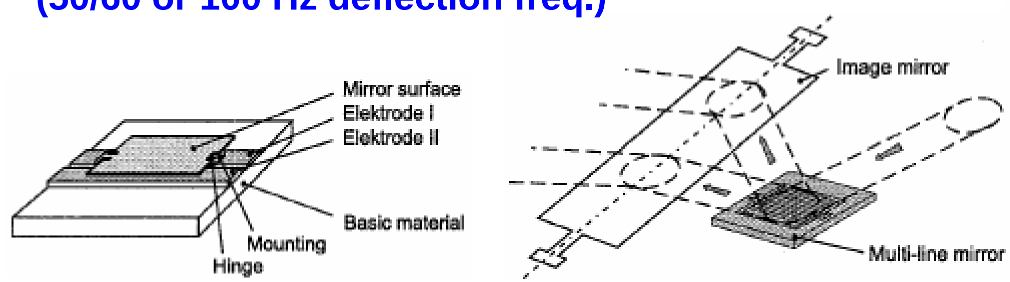
Laser display system (Microscanning mirror)

- ✓ Schneider Rundfunkwerke AG, LDT, Jenoptik (1998)





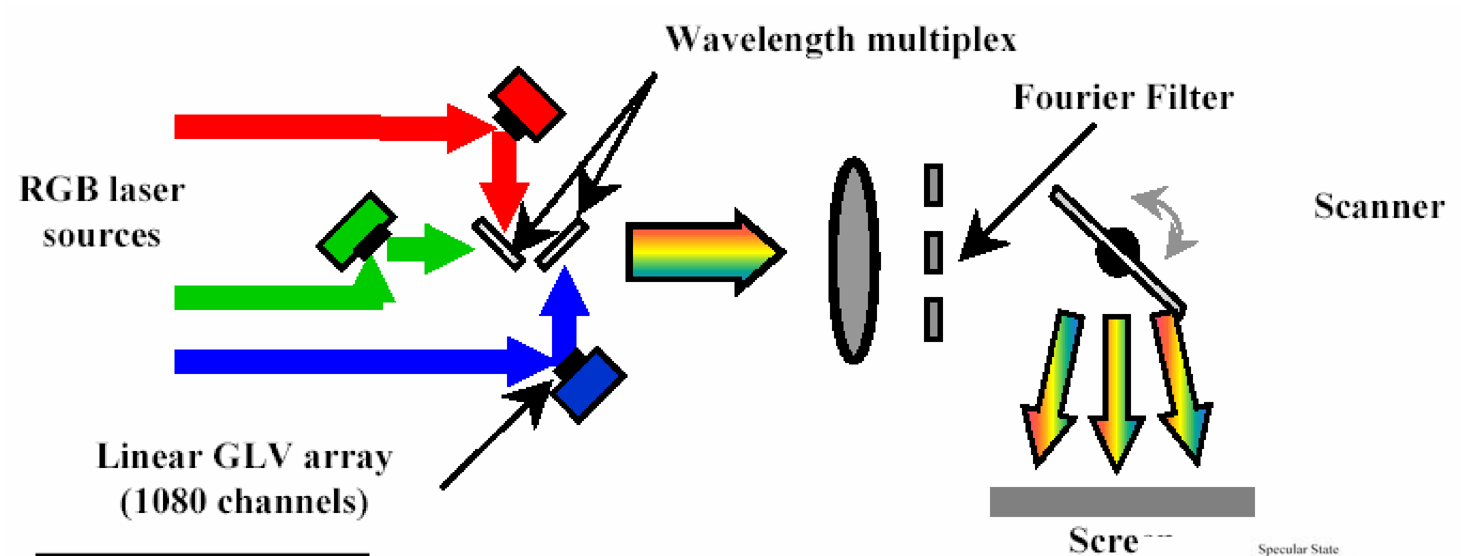
Horizontal deflection: 25-face polygon mirror
(max. 1.3kHz rotation→ 32kHz line deflection freq.)
Vertical deflection: galvanometer scanner
(50/60 or 100 Hz deflection freq.)

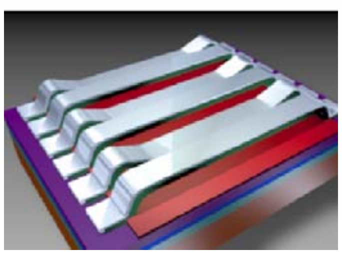


Micro-mirrors

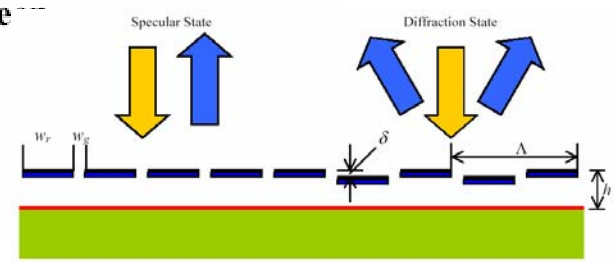
Laser Display System

❑ Laser display system (Grating)





Pixels per Image: 2 x 10^6
Data flow ~ 800Mbit/sec (per GLV)



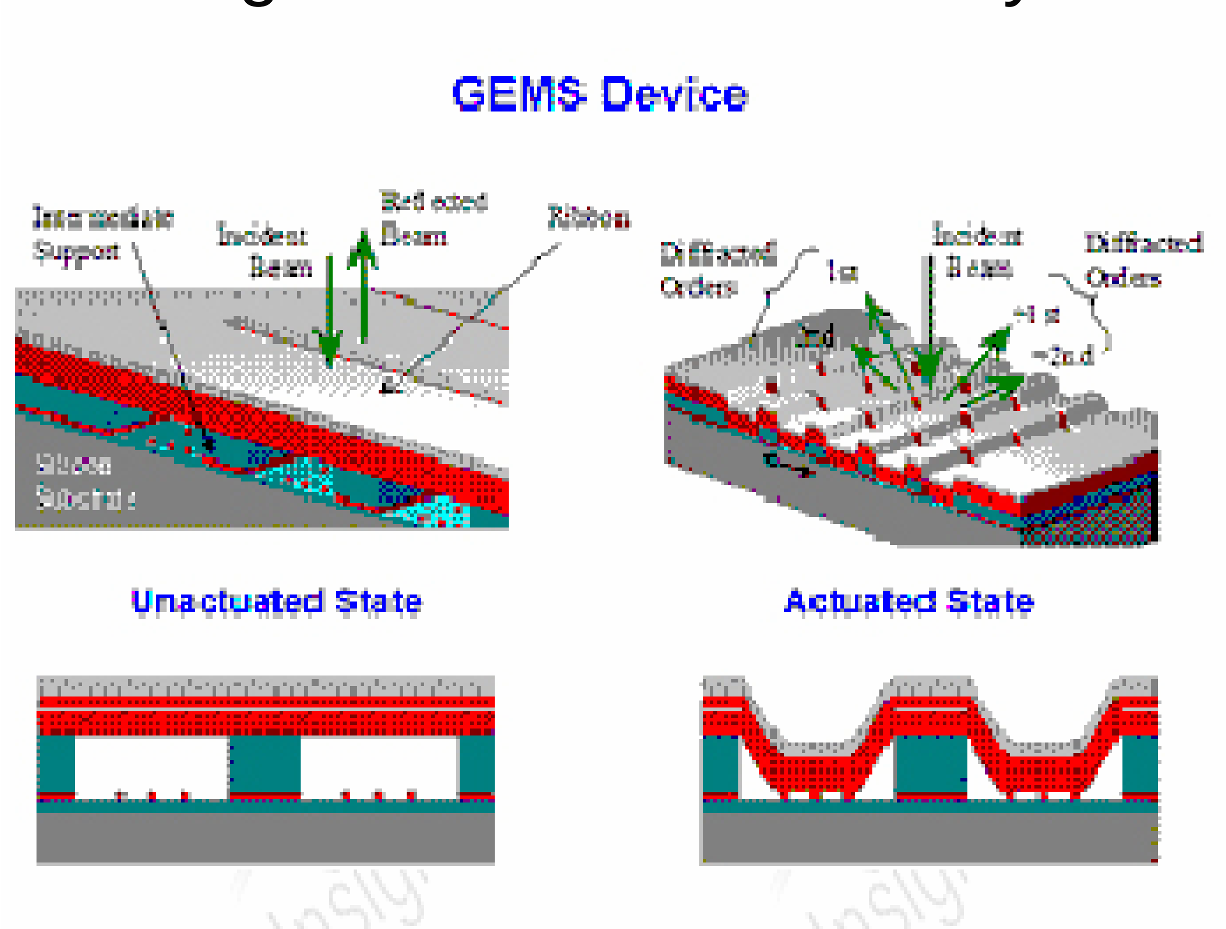
Schematic layout of a GLV-based HDTV projector

- **GLV (Grating Light Valve) – MEMS 1-D spatial light modulator**

  Advantages: High efficiency, large dynamic range, precise analog attenuation, fast switching speed (~1 us), high reliability, high yield, integration

  Static ribbons are interlaced with the electrostatically deflectable ribbons. One or more ribbon-pairs form a pixel. The amount of diffraction can be controlled to impart an 8-bit or better gray-level intensity graduation.

Kodak's Grating Electro Mechanical System (GEMS)



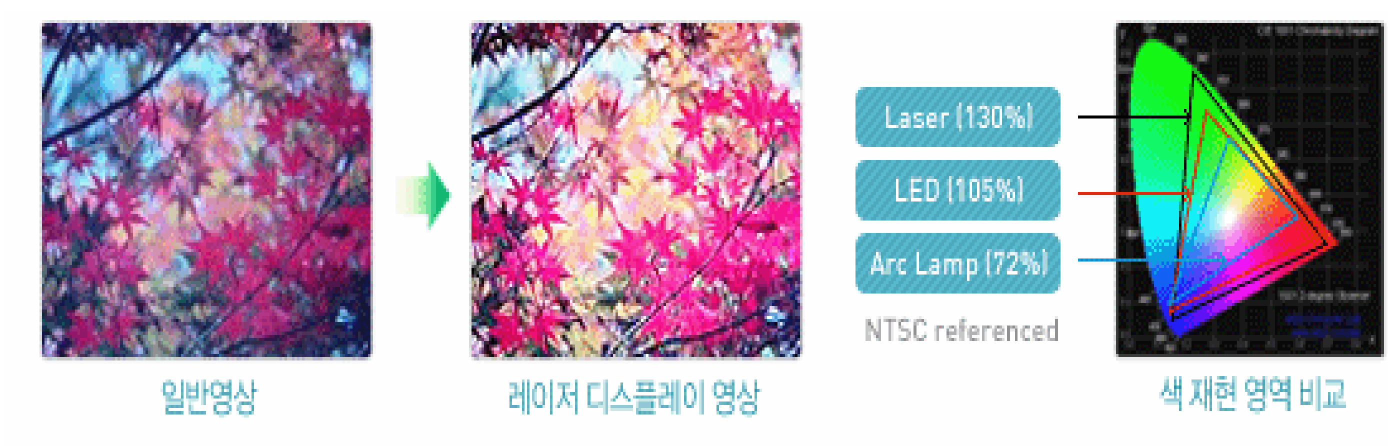
❑ Mitsubishi's Laser Rear Projector Display

(When the technology is finally released to public, which Mitsubishi says will be sometime in late '07, it will be the first ever consumer laser display technology.)

52”

Laser Display System

삼성종합기술원

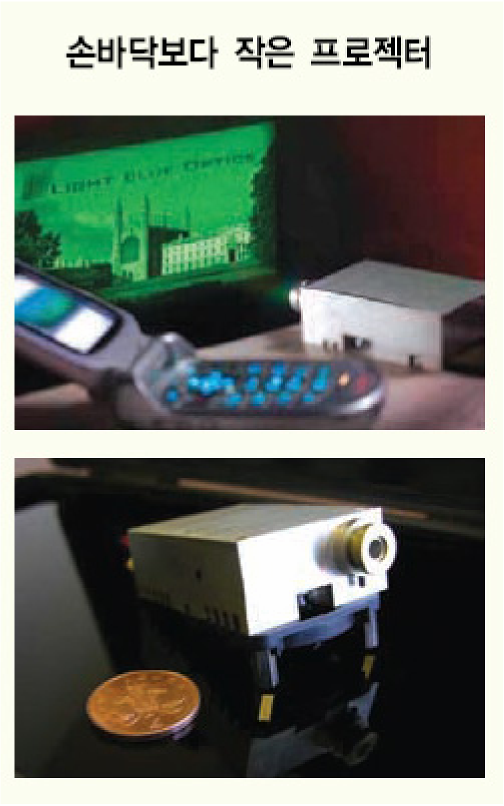


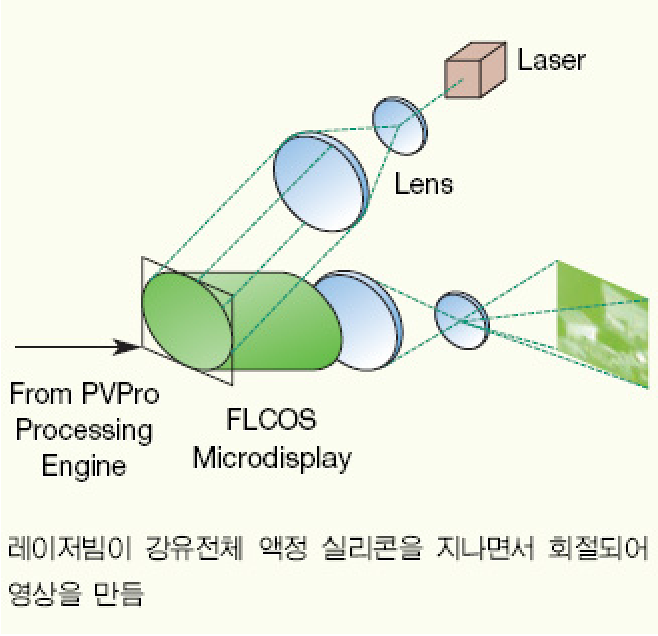
Laser Display System

At CES (2006), Novalux demonstrated two MDTV (microdisplay-based rear-projection TV) laser-based prototypes: a 47-in. 3-LCD (liquid-crystal display) MDTV and a 52-in. MDTV using DLP (digital light processor) technology (see figure). A reference UHP-based MDTV was also shown. The baseline UHP-based MDTV offers about 400 Cd/m^2 of on-screen brightness. The same TV with the laser source offers about 250 Cd/m^2 while the DLP set produces about 300 Cd/m^2.
(Green: 532 nm, 1.5W, Blue: 460 nm, 1.5W, Red: 635nm)

Laser Display System

❑ Light Blue Optics
(PVPro: Ferroelectric Liquid-Crystal-On-Silicon)





❑ Univ. of Southampton – High Power Fiber Laser Display

- **Advantages of Laser Projection Display**

  Increased color gamut

  Quasi-parallel (collinear) rays

  - No focusing is necessary.

  - Projection on non-plane surfaces is simple.

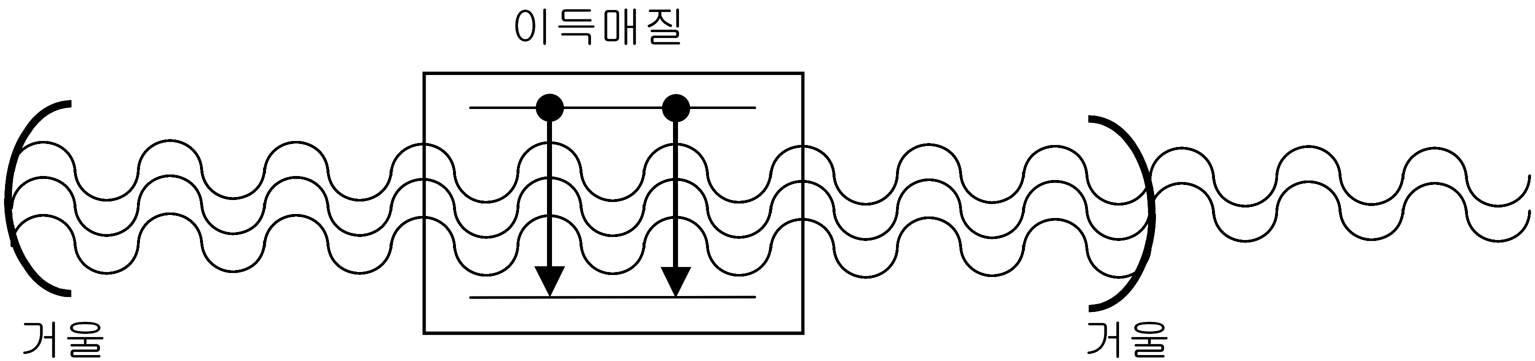
- **Difficulties**

  Small, high-power, cheap lasers

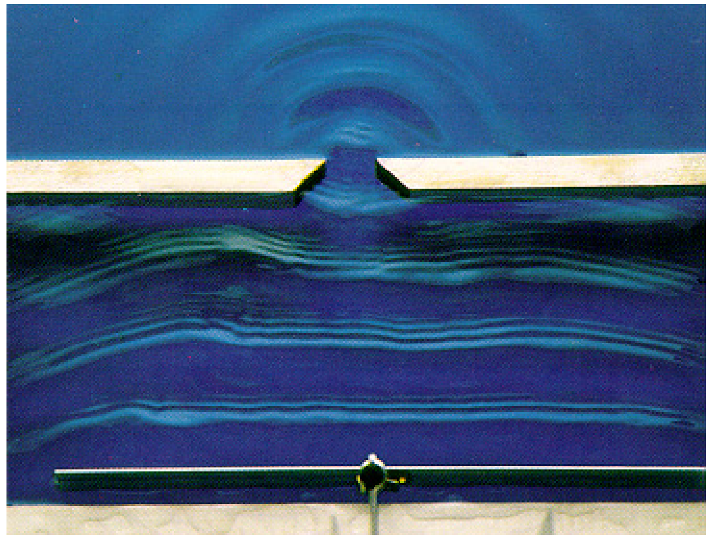
  Speckles

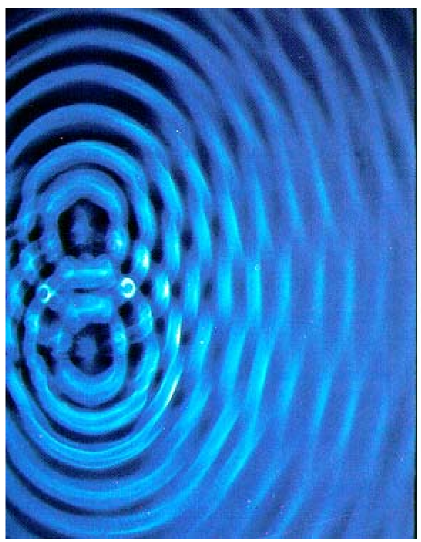
Laser

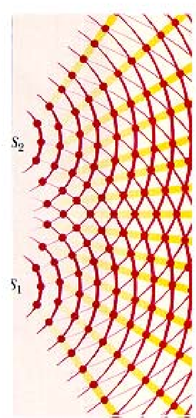
Light Amplification by Stimulated Emission of Radiation

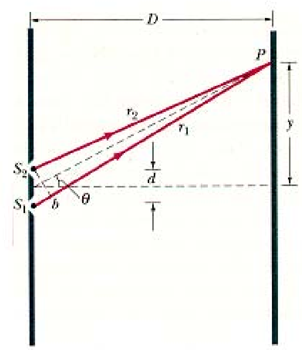


Diffraction and Interference

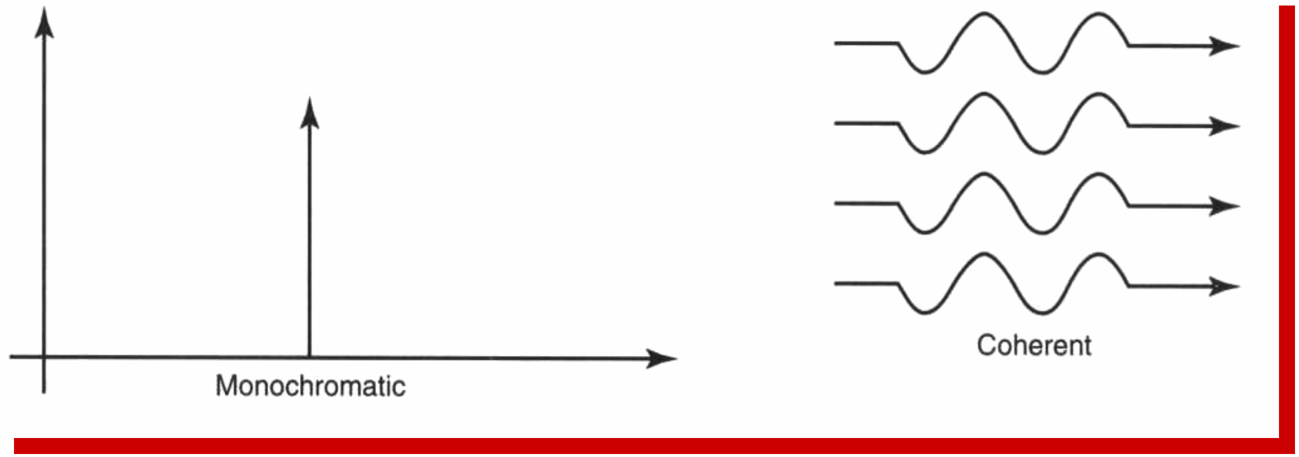




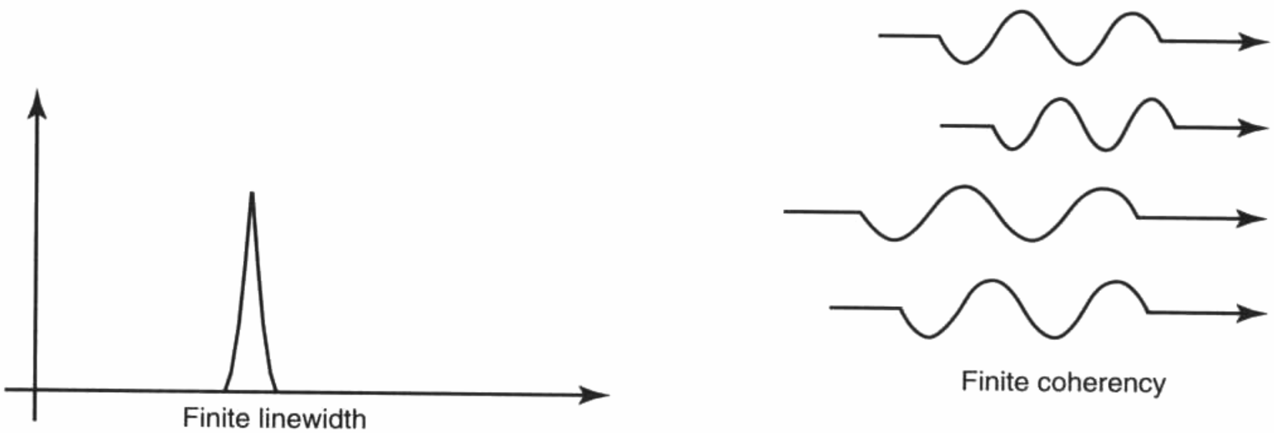




Coherency and Spectrum

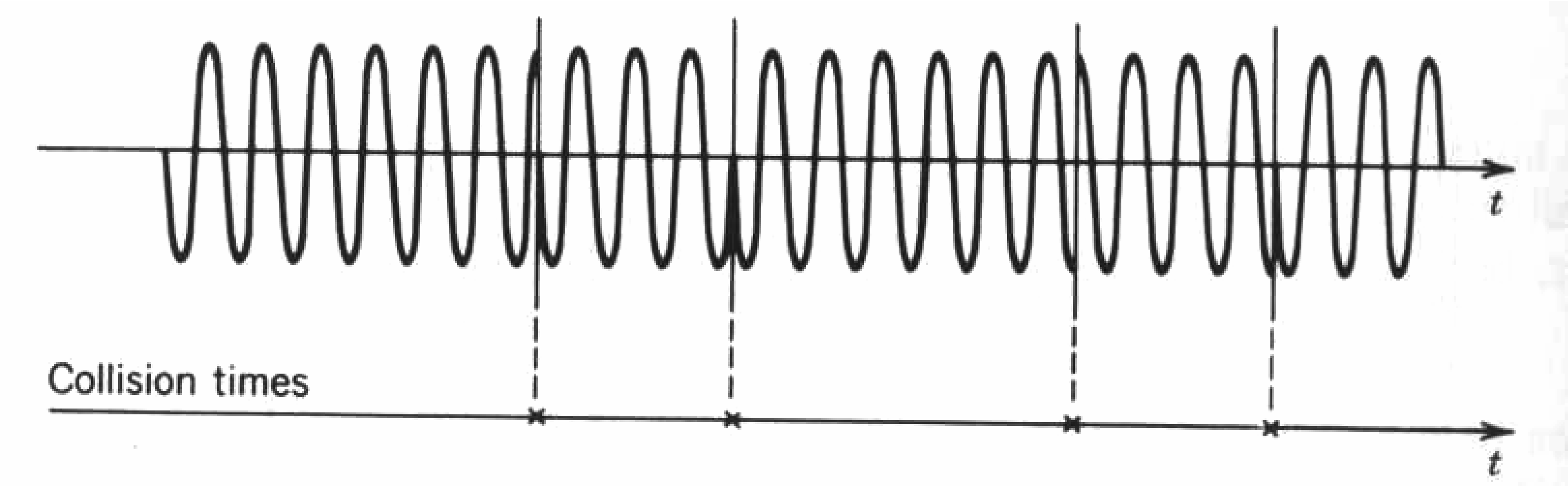


An ideal monochromatic source of light has a group of photons with exactly one frequency.
An ideal coherent source of light has a group of photons with the same relative phase.



Real laser sources are neither perfectly monochromatic nor perfectly coherent.
A real laser will have a finite linewidth and finite coherency.

Coherence Time and Coherence Length

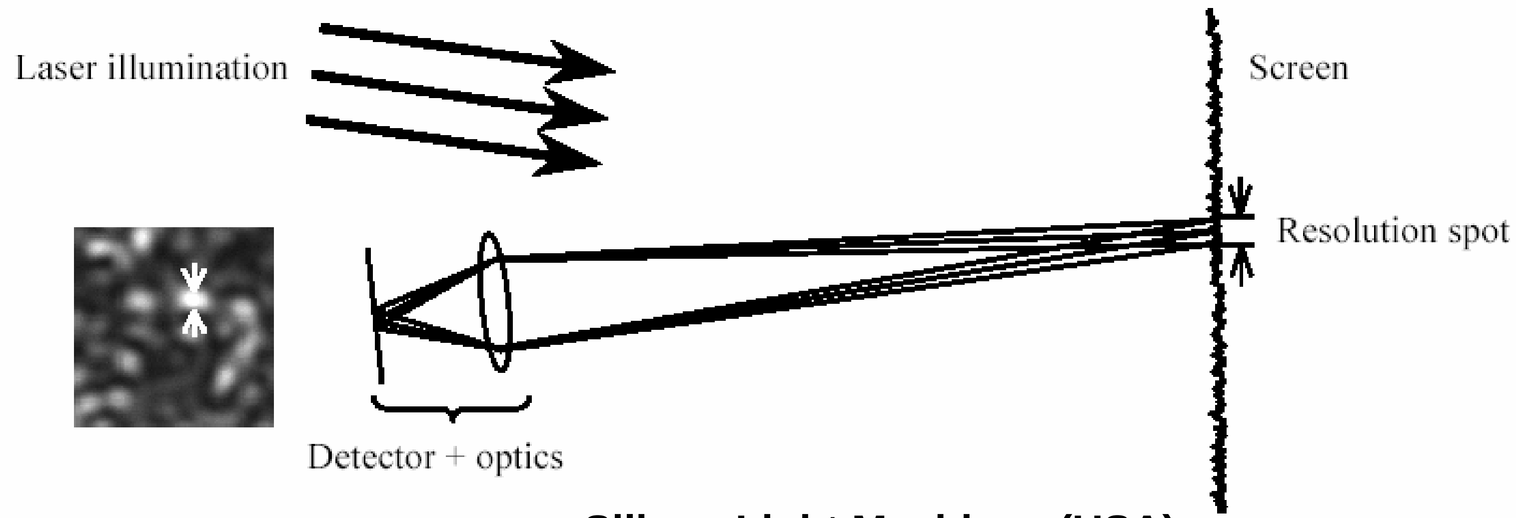


$$\Delta\nu = \frac{1}{2\pi}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + 2 f_{\mathrm{col}}\right)$$

Speckles

❑ Static speckle noise generation in laser displays

- ✓ Coherent laser beam is scattered on a spot in a rough screen surface.
- ✓ Complex interference pattern (speckle) is detected by a detector (CCD, human eye).
- ✓ Static speckle image masks the displayed image information.

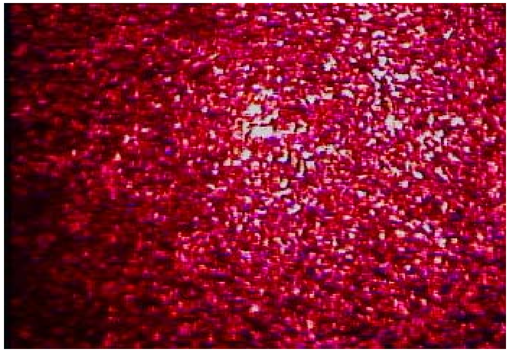


Silicon Light Machines (USA)

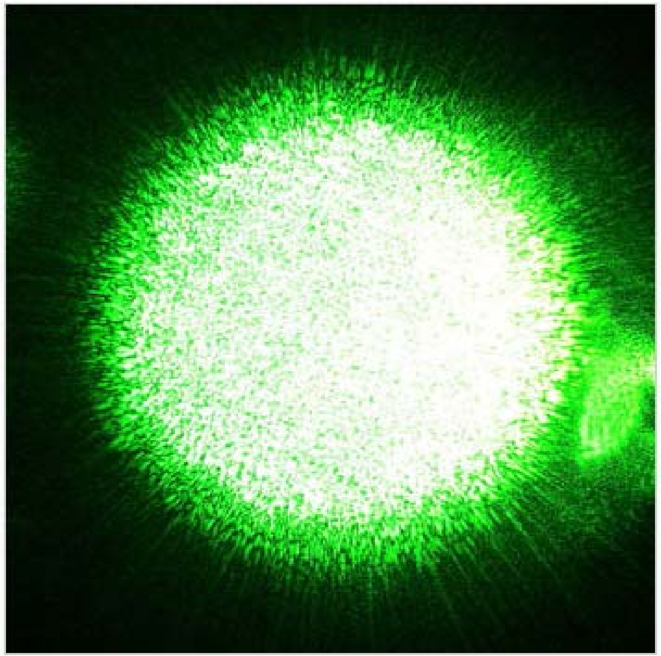
Speckle grain size is inversely proportional to beam spot radius.

Some Speckle Patterns

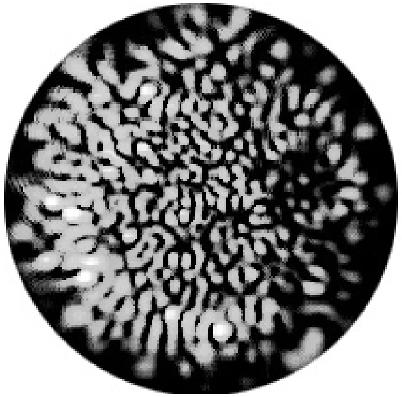
Ground Glass



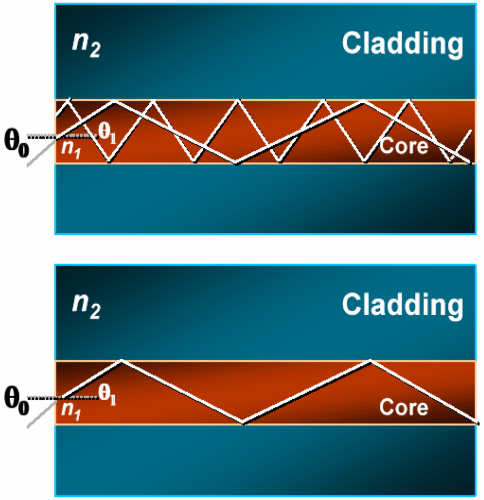
Gray-level Film



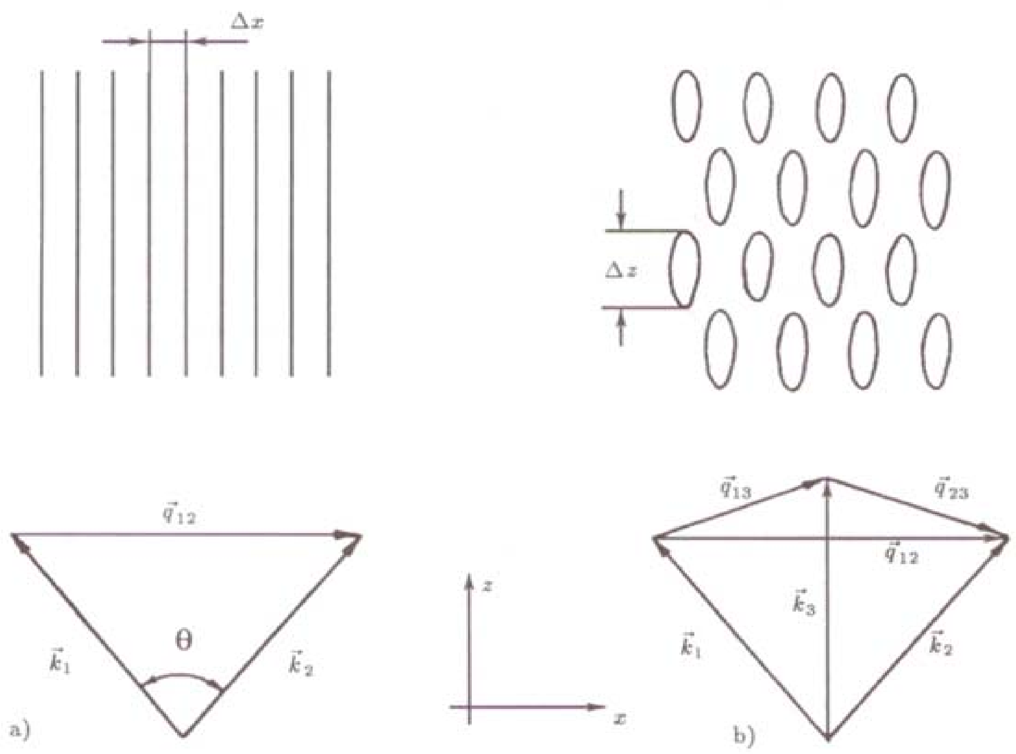
Laser pointer spot
on a screen



Multimode Fiber



Speckle Size 1



$$\Delta x = \frac{2\pi}{K}$$

$$K = 2k\sin\left(\frac{\theta}{2}\right) \approx k\theta = \frac{2\pi}{\lambda}\theta$$

(for small θ)

$$\Delta x \approx \frac{\lambda}{\theta}$$

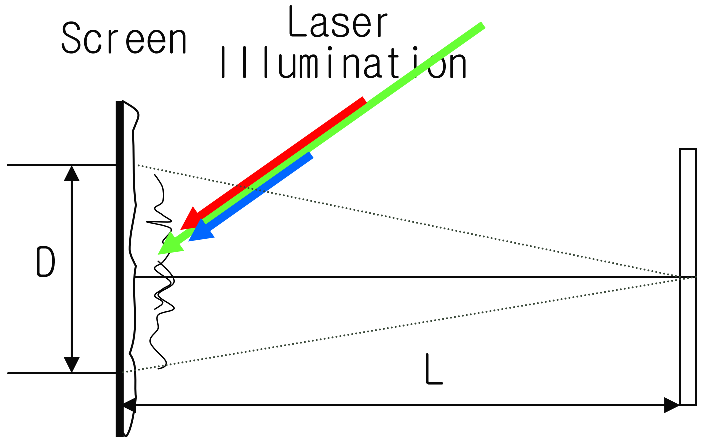
$$\Delta z \approx \frac{\Delta x}{\theta} \approx \frac{\lambda}{\theta^2}$$

Speckle Size 2

❑ Overview of the speckle

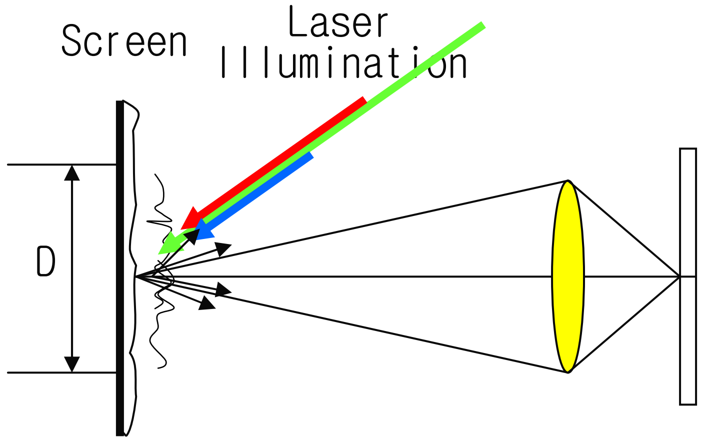
Objective speckle

$$\langle \sigma_o \rangle \cong 1.2\lambda L / D$$



Subjective speckle

$$\langle \sigma_0 \rangle \cong 0.6\lambda / NA$$



Speckle reduction methods

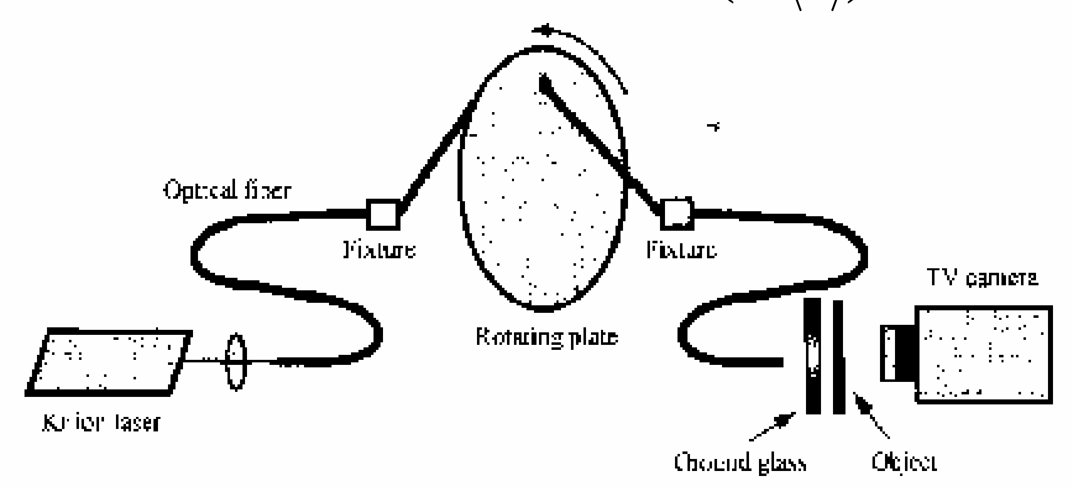
- ✓ The speckle patterns impair the image quality.
    - Strong deblurring of the color edges
  - – Degradation of spatial or temporal coherence (after-image effect) of the laser
    - Degradation of spatial coherence
    - Insertion of various optical components, such as diffractive diffuser, refractive lens arrays, fiber bundle, vibrated components
    - Moving random mask or rotating circular aperture
    - Vibrational change of relative positions of a screen and an illuminating laser beam
    - Movie-like generation of collimated beams with complex phase structures using dynamic SLM
    - Laser beam is widely diffused when its spatial coherence is decreased.
  - – Digital image processing (spatial averaging) of the detected image

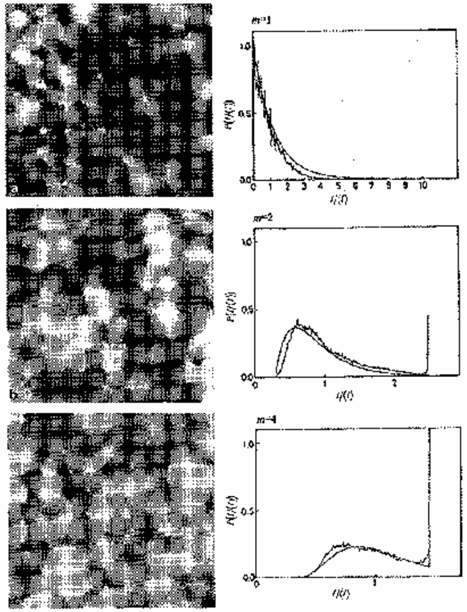
Speckle Reduction 1

❑ Speckle reduction using multimode fiber

- ✓ The laser light transmitted through a multimode optical fiber shows a speckle phenomenon due to the interference between propagation modes in the fiber.
- ✓ The probability density function (PDF) can be defined for speckle contrast ratio.

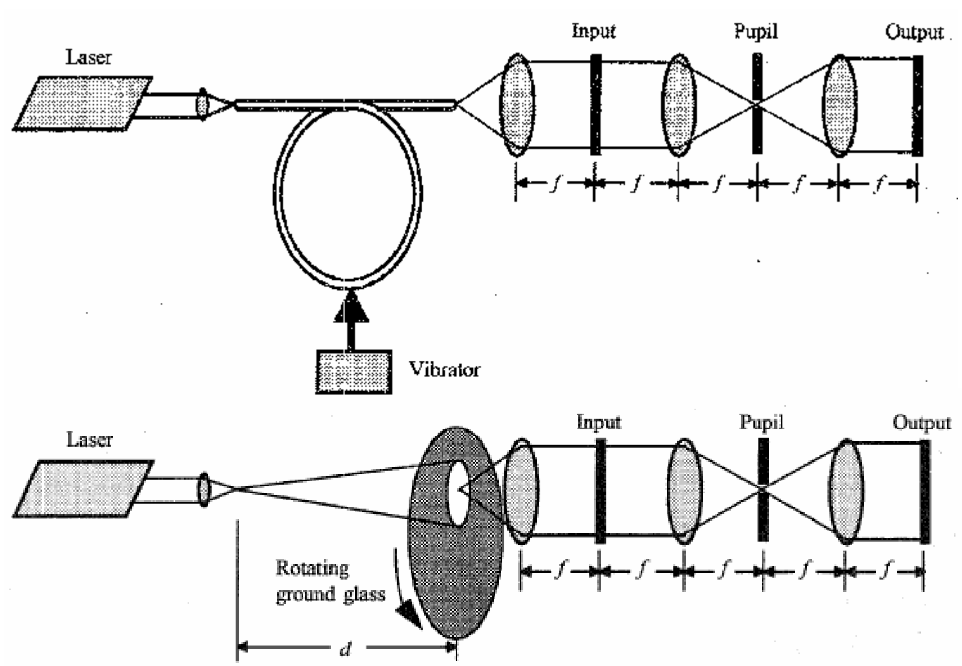
$$CR = P(I/\langle I \rangle)$$

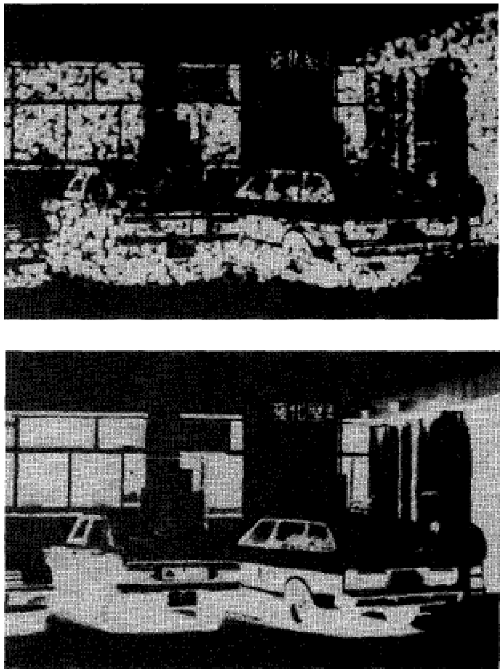




(a) Rotating multimode fiber (b) Theoretical PDF w.r.t. multiple image averaging

- **Speckle reduction using multimode fiber or ground glass**
  - ✓ A vibrating multimode fiber and a rotating ground glass are imaged in the telecentric two-lens imaging system.





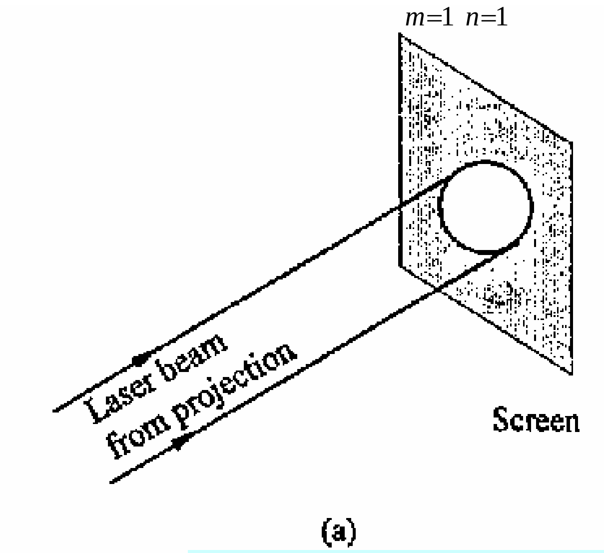
(a) Vibrating multimode fiber and rotating ground glass (b) Experimental result

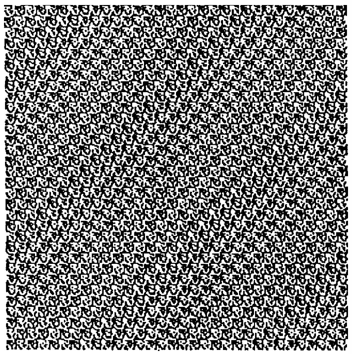
Speckle Reduction 3

❑ Speckle reduction using DOE

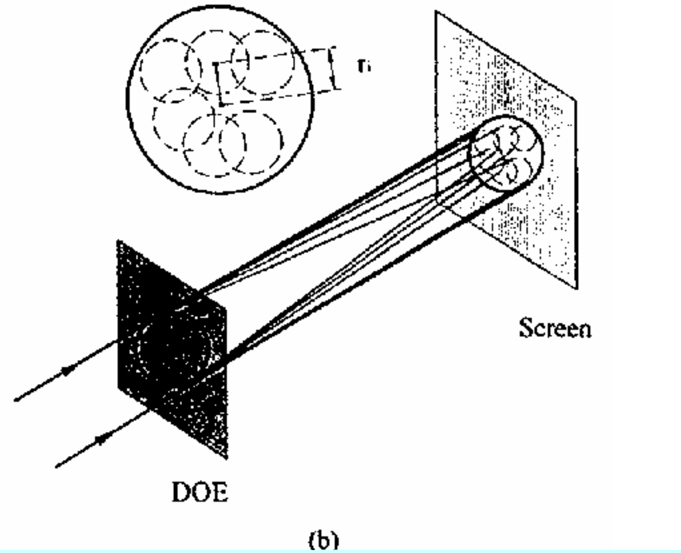
- ✓ Splits the unfocused laser beam into a number of independent beamlets with random phase distribution
- ✓ Smaller diameter than the original beam
- ✓ Multi-level phase structure DOE using IFTA

$$f(x,y)=\sum_{m=1}^{M}\sum_{n=1}^{N}A_{mn}\exp(i\phi_{mn})\delta(x-x_m,y-y_n)$$





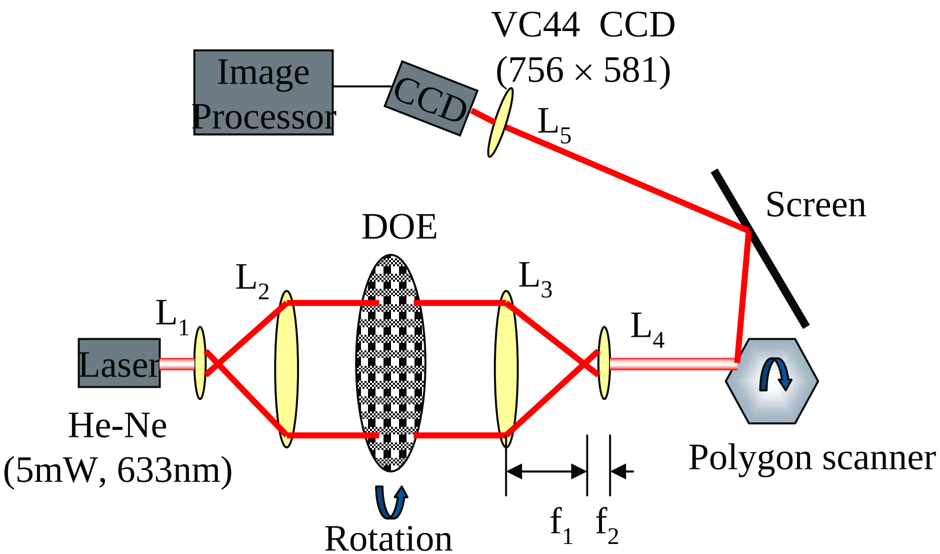
Designed binary DOE structure

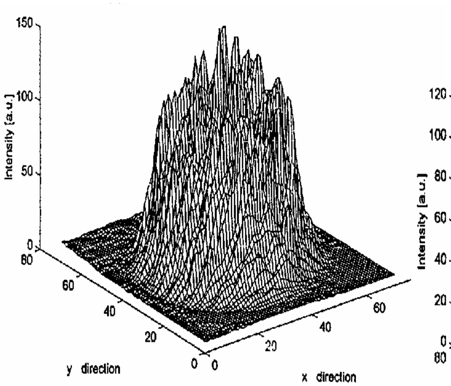


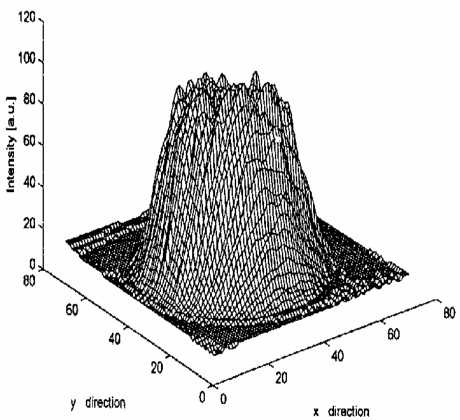
(a) Laser beam from projection (b) Beamlets coming from the DOE

❑ Speckle reducing using rotating DOE

- ✓ Rotating a collimated diffractive beam (after-image effect)







Experimental setup and result (a) with a static DOE (b) with a DOE rotating at a speed of 5 rps

Speckle Reduction 5

❑ Speckle reduction using moving diffuser

- ✓ Without diffuser: no speckle reduction
  - – Speckle intensity of the resolution spot $S_0 = \left|\sum_{i=1}^{M}\sum_{j=1}^{N} E_{ij}\right|^2$
- ✓ Diffuser imprints N=M×M cells with relative phase ϕ_{ij}^{a}
  - – A different pattern is sequentially presented with equal duration during the detector integration time.

$$S = \frac{1}{A}\sum_{a=1}^{A}\left|\sum_{i=1}^{M}\sum_{j=1}^{N} H_{ij}^{a} E_{ij}\right|^2 \qquad H_{ij}^{a} = \exp\left(i\phi_{ij}^{a}\right)$$

  - – The summation of H_{ij}^{a} over all the phase patterns satisfies the decorrelation condition.

$$\sum_{a=1}^{A} H_{ij}^{a^*} H_{kl}^{a} = A\delta_{ik}\delta_{jl}$$

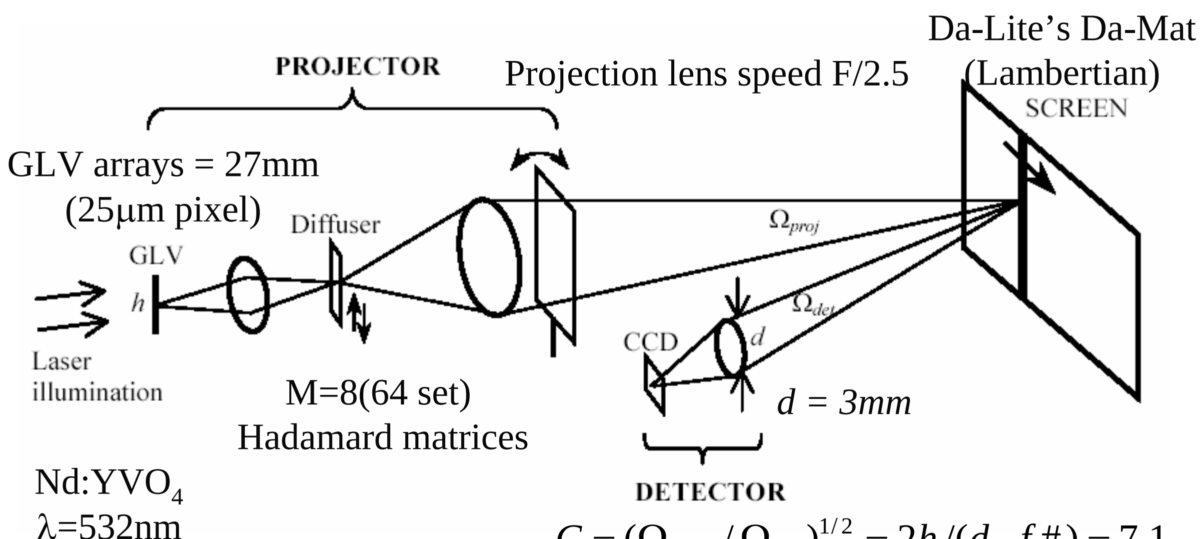
Hadamard matrices of order M=$2^{integer}$ satisfies this condition

$$S = \frac{1}{A}\sum_{a=1}^{A}\left|\sum_{i=1}^{M}\sum_{j=1}^{N} H_{ij}^{a} E_{ij}\right|^2 = \frac{1}{A}\sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{l}\left(H_{ij}^{a^*} E_{ij}^{*}\right)\left(H_{kl}^{a} E_{kl}\right) = \sum_{i}\sum_{j}\left|E_{ij}\right|^2$$

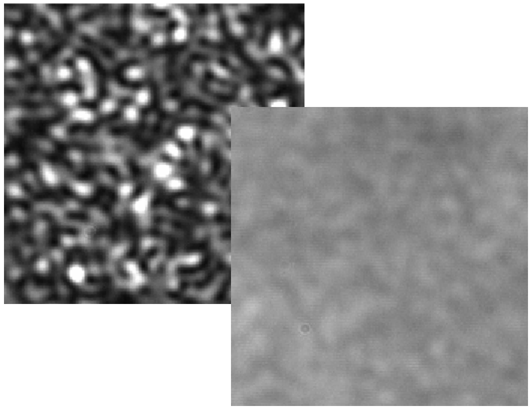
  - – Speckle contrast is reduced by a factor of R_Ω = M ×M.

❑ Speckle reduction using moving diffuser

- ✓ GLV™ (Grating Light Valve) array is a unique MEMS-based, 1-D SLM that modulates light by diffraction
  - – High efficiency, large dynamic range, precise analog attenuation, fast switching speed(1μsec), high reliability, high yield, and high resolution.
- ✓ Hadamard diffuser suppressed speckle contrast to 8%.



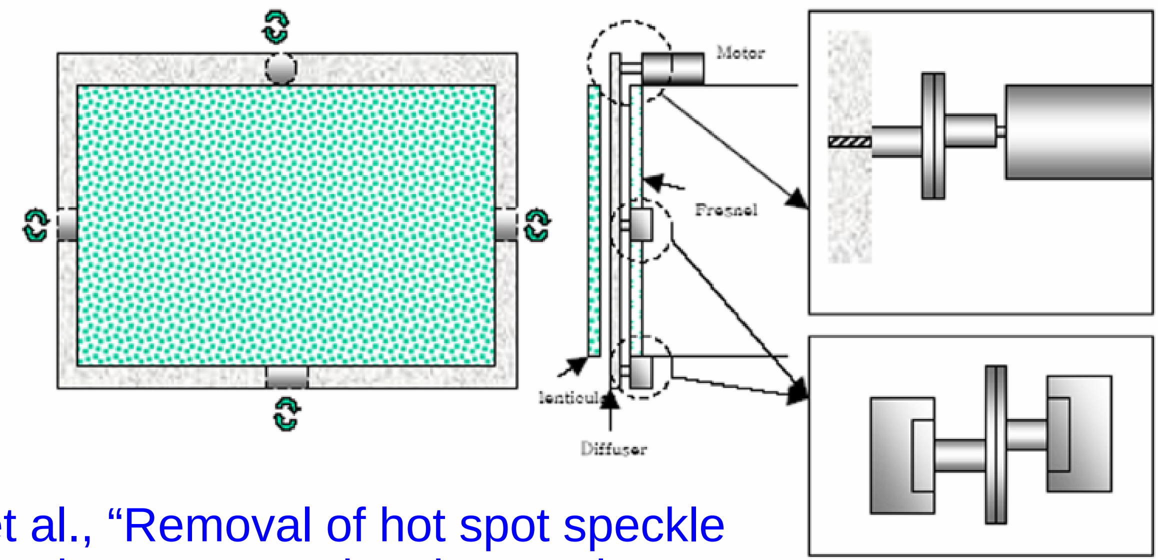
$$C = (\Omega_{proj} / \Omega_{det})^{1/2} = 2h/(d \cdot f\#) = 7.1$$



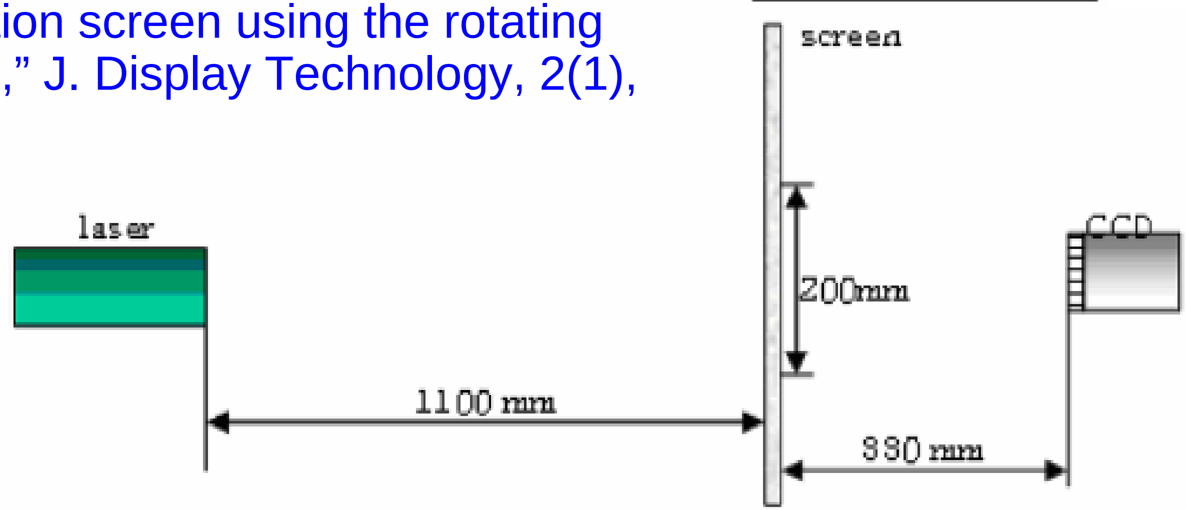
(a) Original speckle (70% contrast)
(b) Reduced speckle (8% contrast)

Silicon Light Machines (USA)

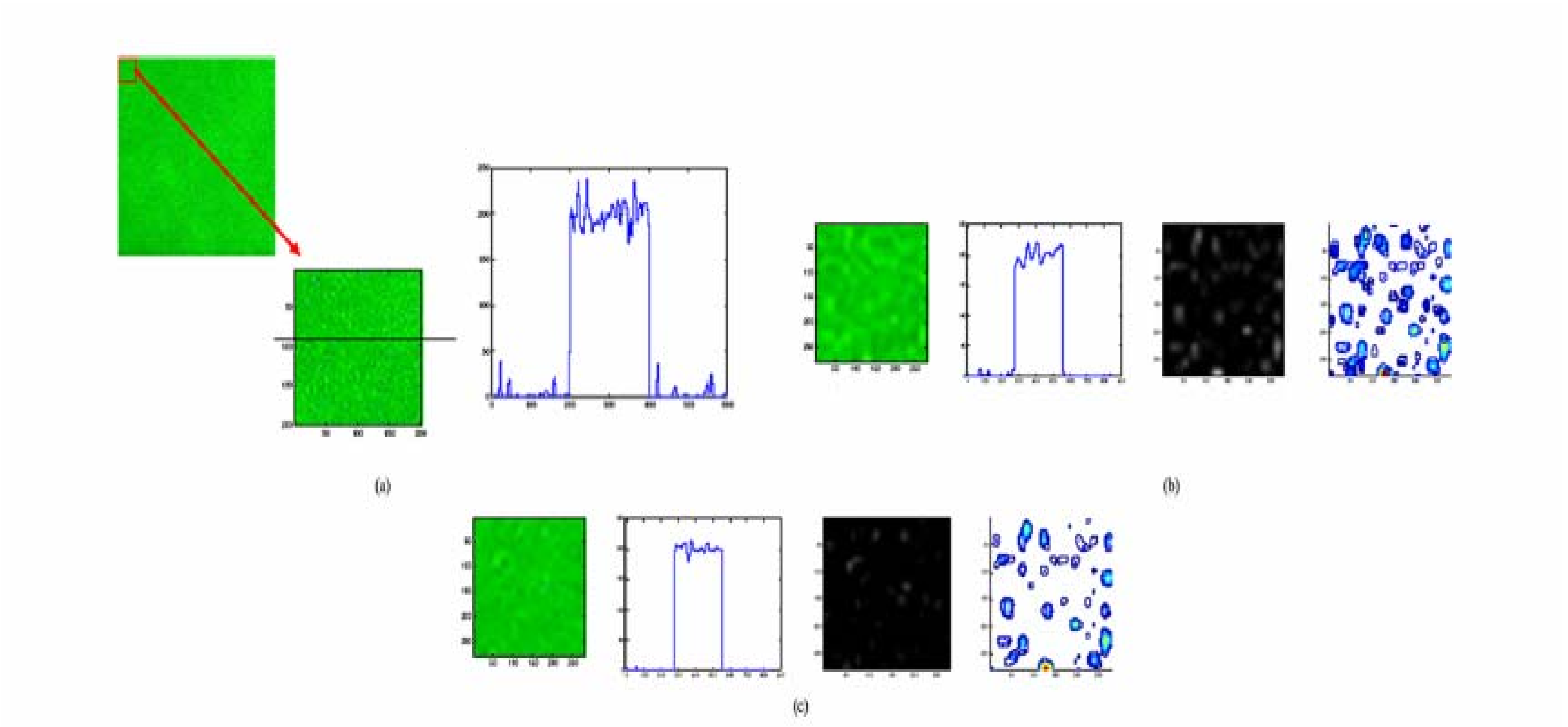
Speckle Reduction 7 – LG Electronics



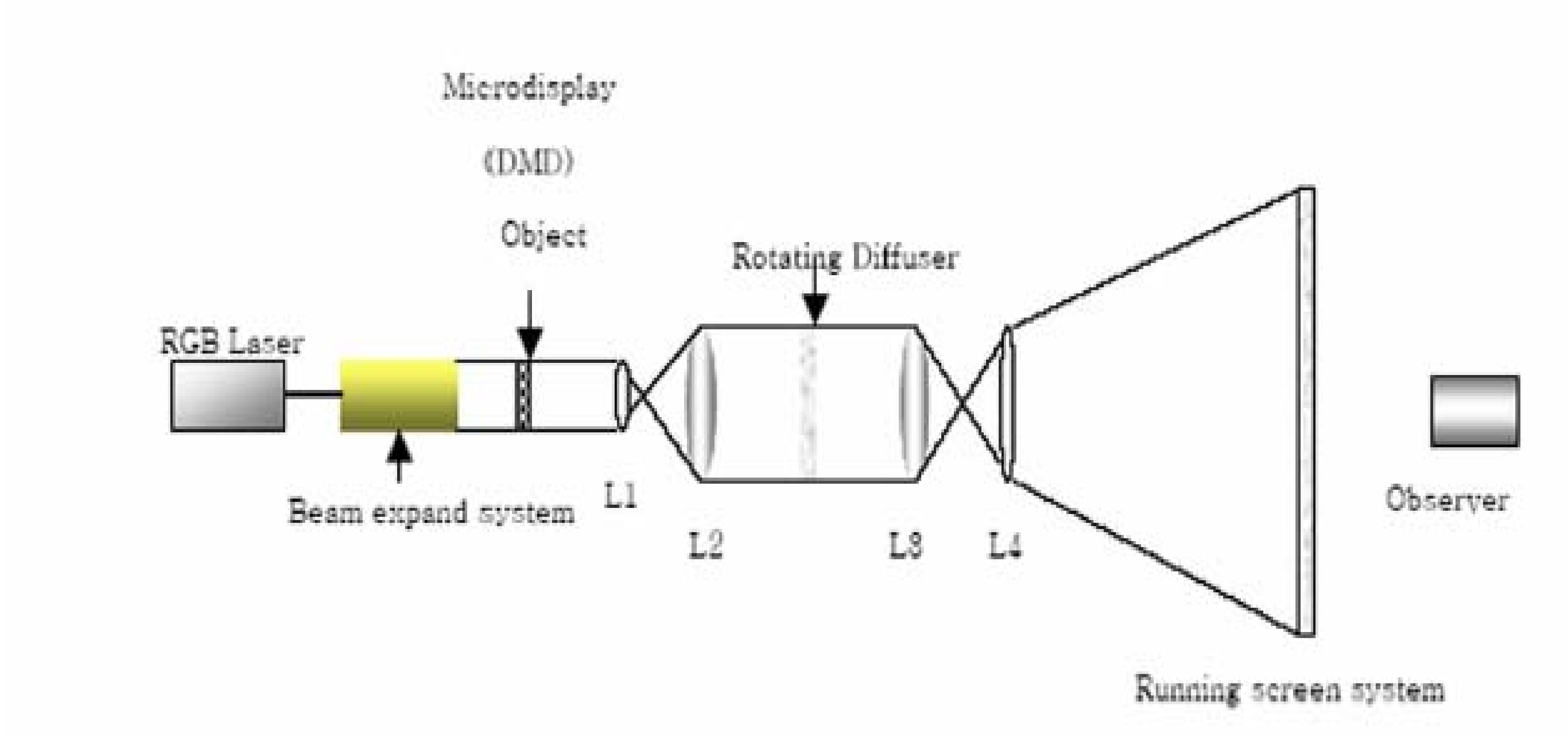
S. C. Shin et al., “Removal of hot spot speckle on rear projection screen using the rotating screen system,” J. Display Technology, 2(1), 79-84, 2006.



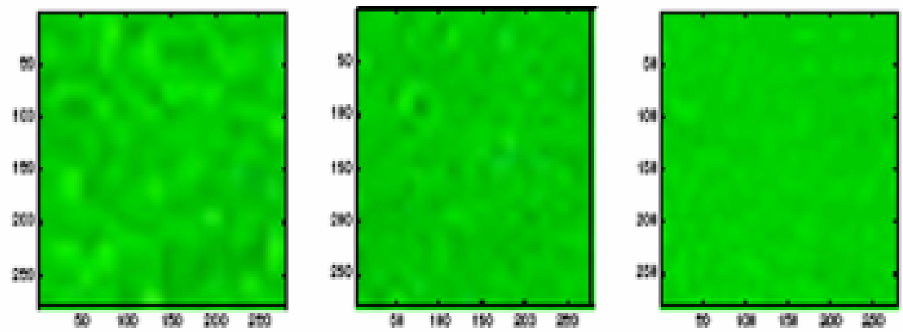
Speckle Reduction 7 – LG Electronics



Speckle Reduction 7 – LG Electronics



Speckle Reduction 7 – LG Electronics

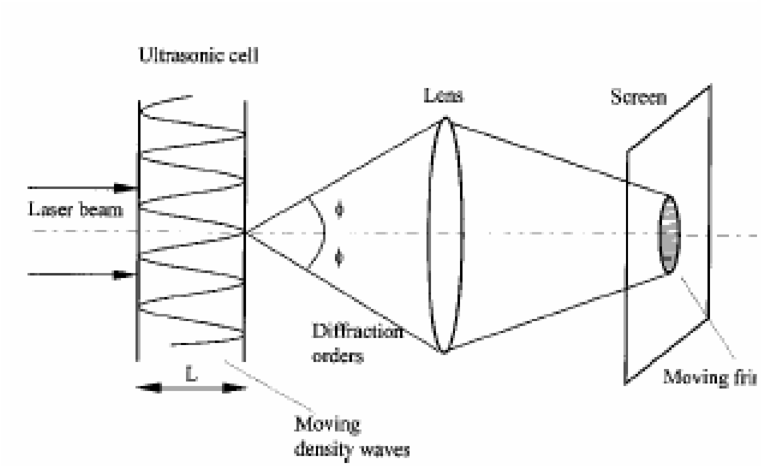


(A) (B) (C)

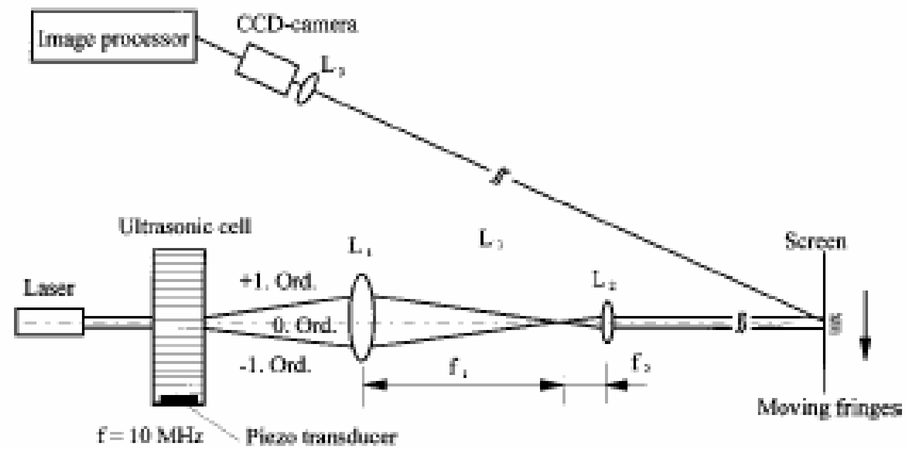
Rotating Diffuser	NONE	USE	USE
Running Screen	NONE	NONE	USE
Speckle Contrast(%)	6.5	3.1	1.6

70”

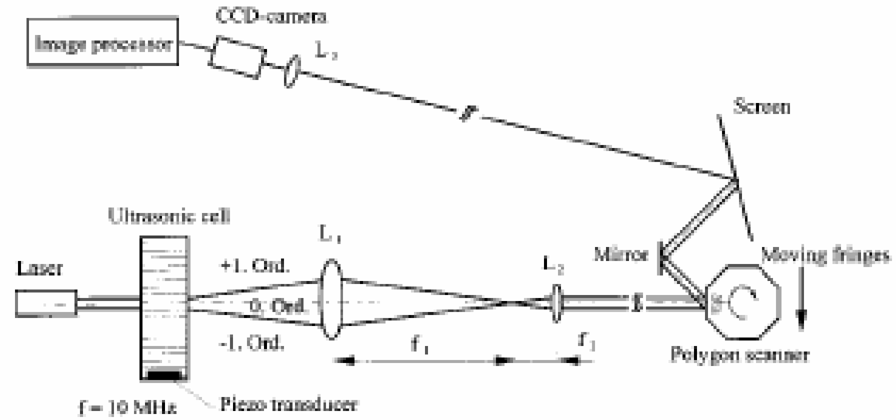
Speckle Reduction 8



Toluene ($CH_3C_6H_5$) cell



(a)



(b)

L. Wang et al., "Speckle reduction in laser projections with ultrasonic waves," Opt. Eng., 39(6), 1659-1664, 2000.

Speckle Reduction 8

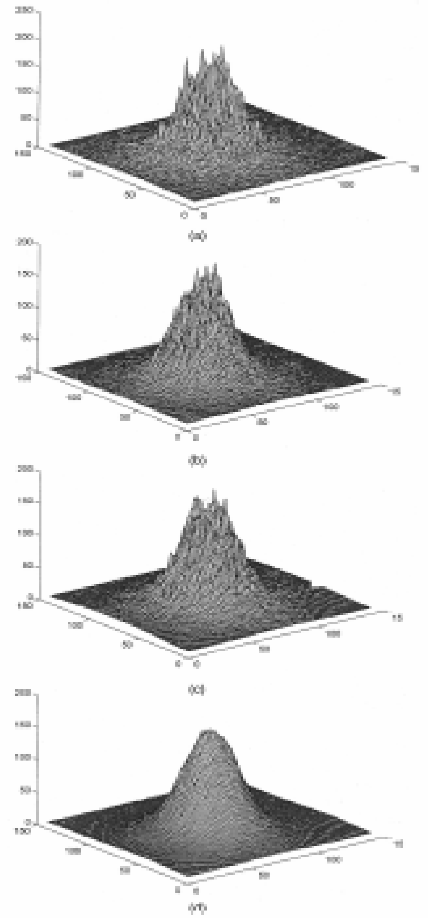


Fig. 4 Speckle contrast measured with the arrangement shown in Fig. 3(a): (a) with only the argon laser (wavelength 514 nm, diameter 0.5 cm, power 1.5 W), (b) with one ultrasonic cell (2.2 MHz), (c) with two cells (2.2 and 10.0 MHz), (d) with three cells (2.2, 3.3, and 10.0 MHz).

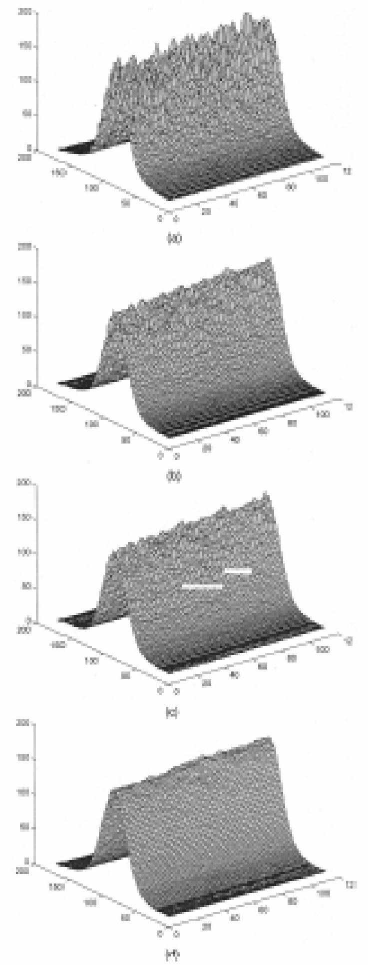
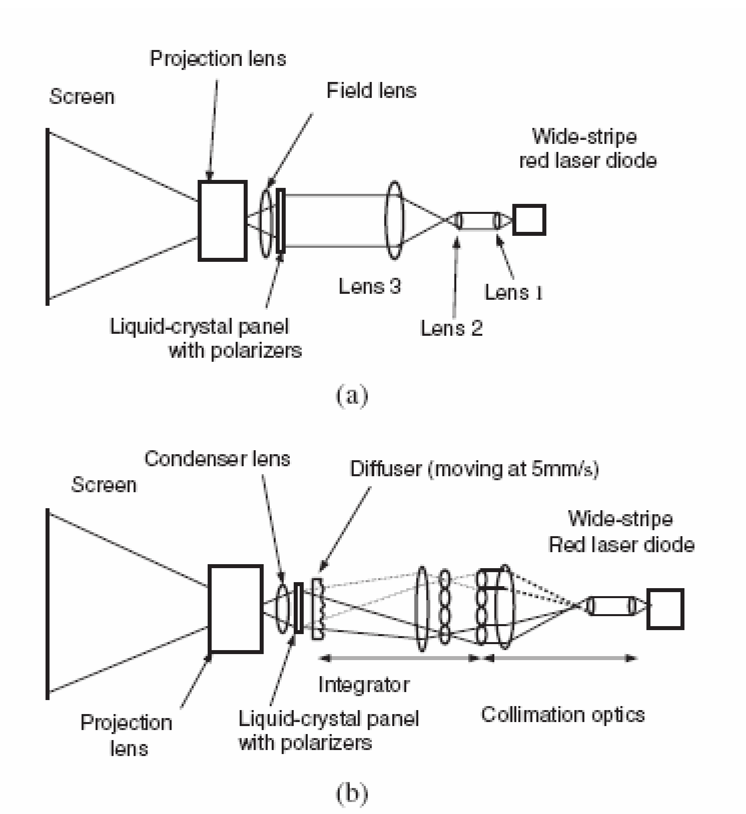
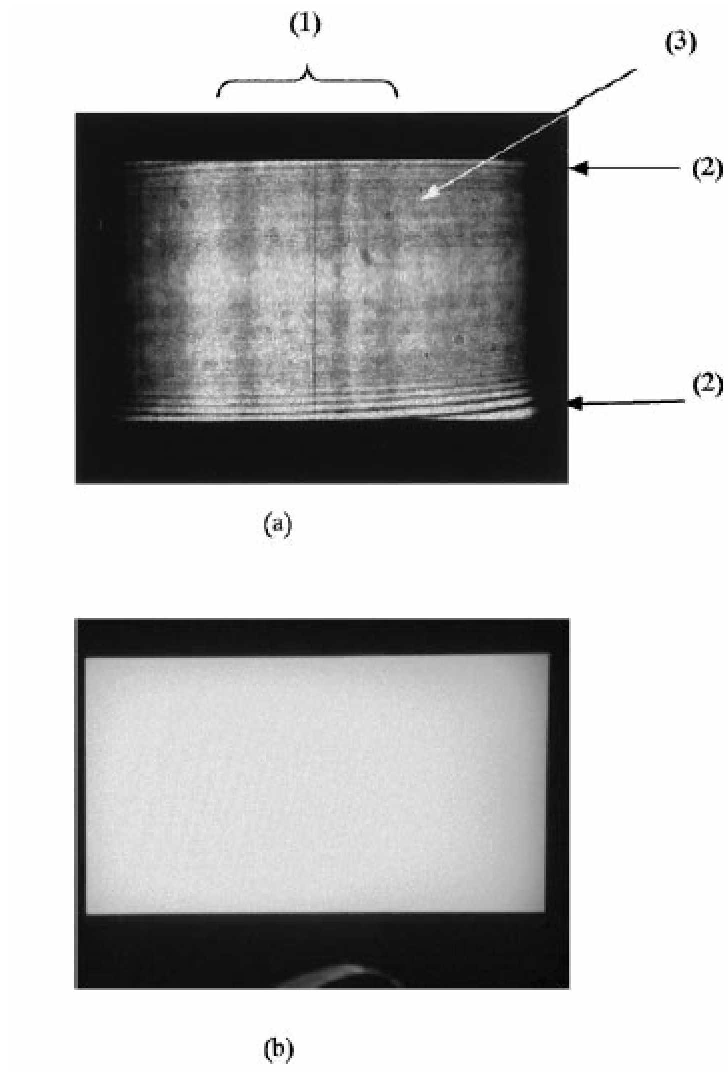


Fig. 5 Speckle contrast measured with the arrangement shown in Fig. 3(b): (a) with only the argon laser (wavelength 514 nm, diameter 0.5 cm, power 1.5 W), (b) with one cell (2.2 MHz), (c) with two cells (2.2 and 10.0 MHz), (d) with three cells (2.2, 3.3, and 10.0 MHz).

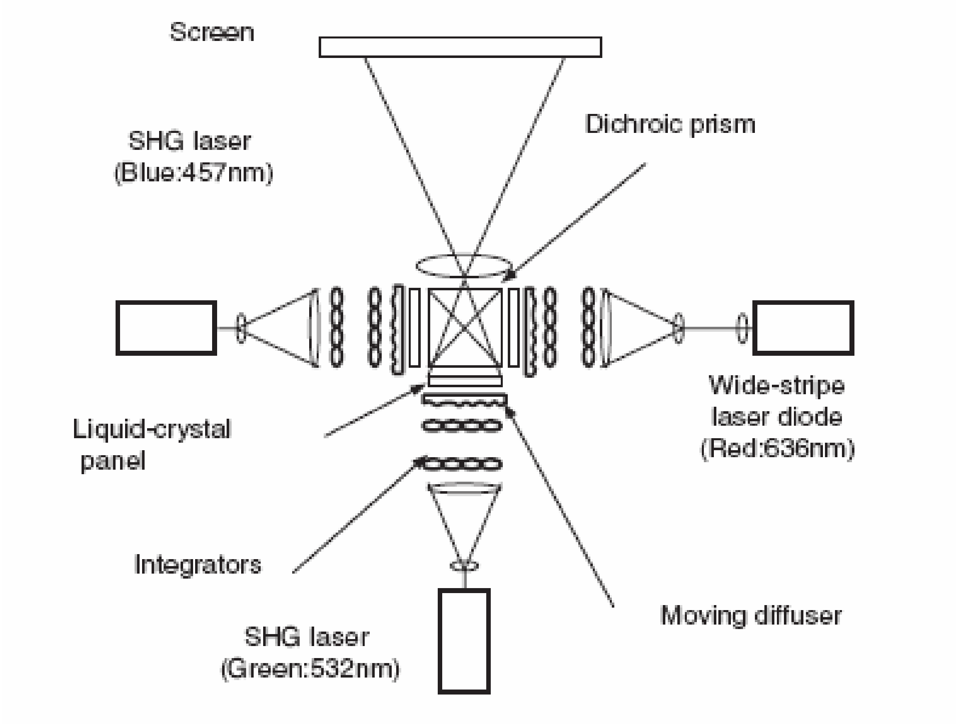
Speckle Reduction 9

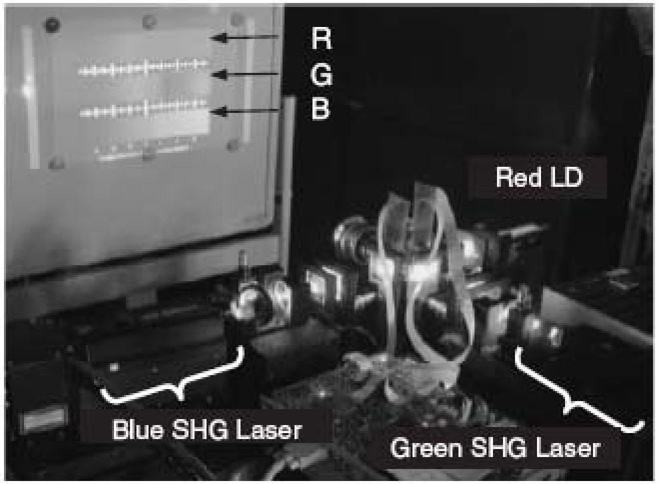




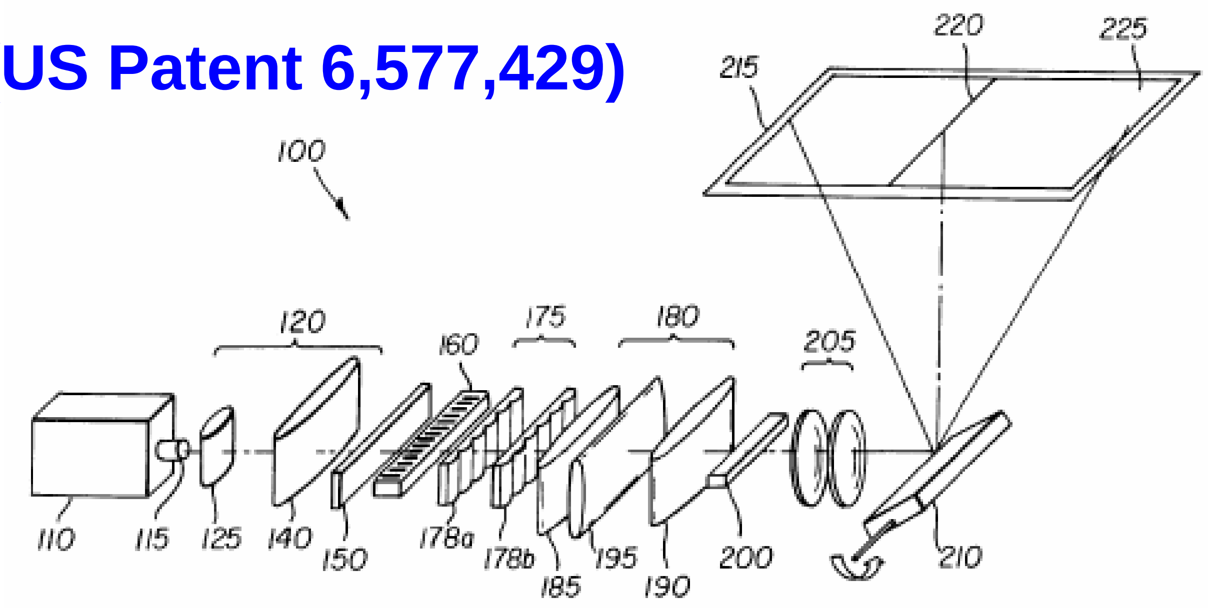
K. Kasazumi et al., Jpn. J. Appl. Phys., 43(8B), 5904-5906, 2004.

Speckle Reduction 9





Kodak (US Patent 6,577,429)



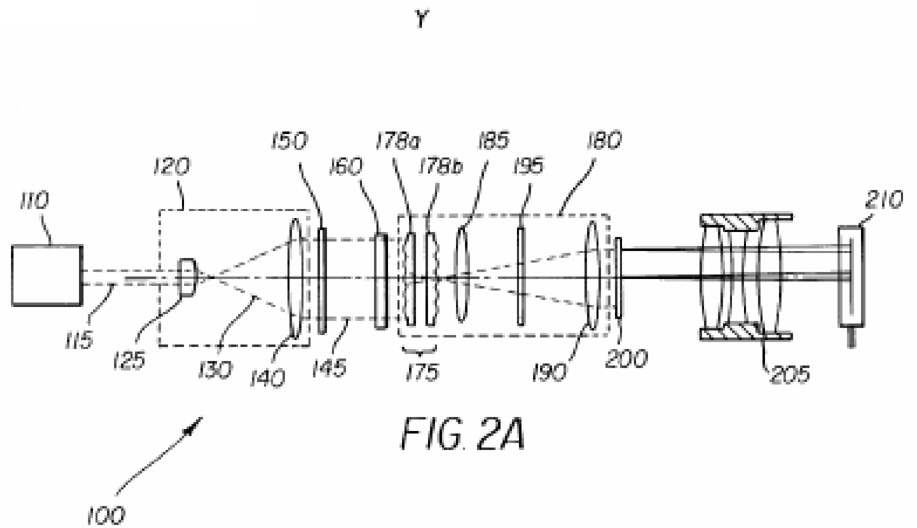
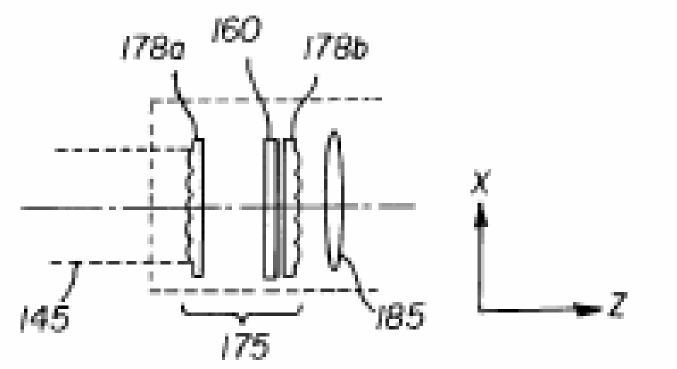
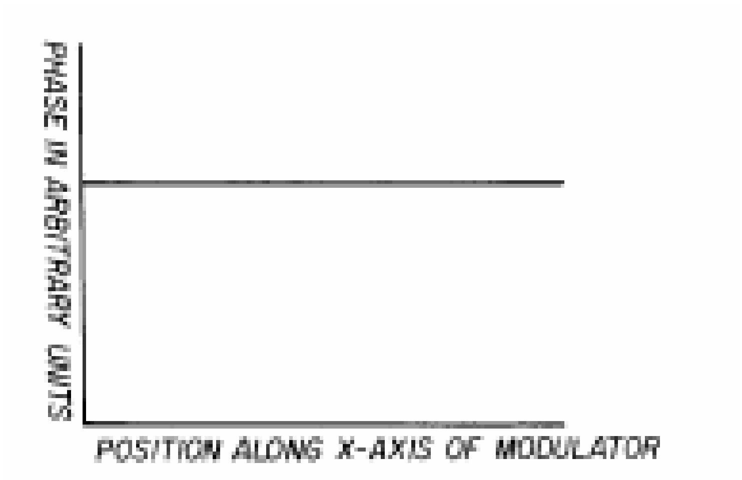
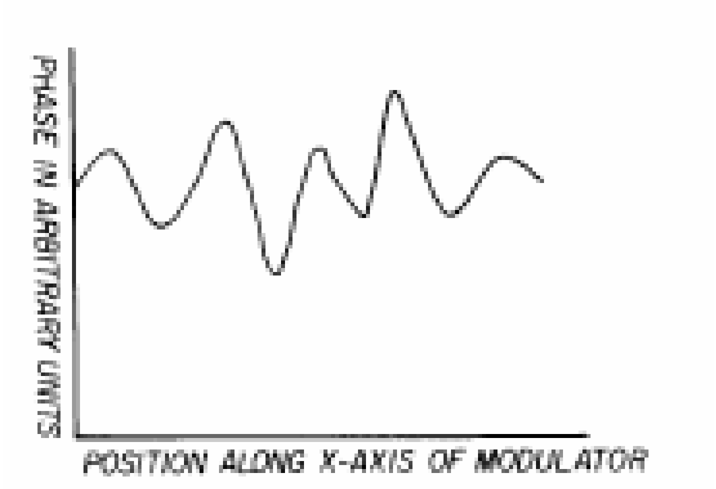


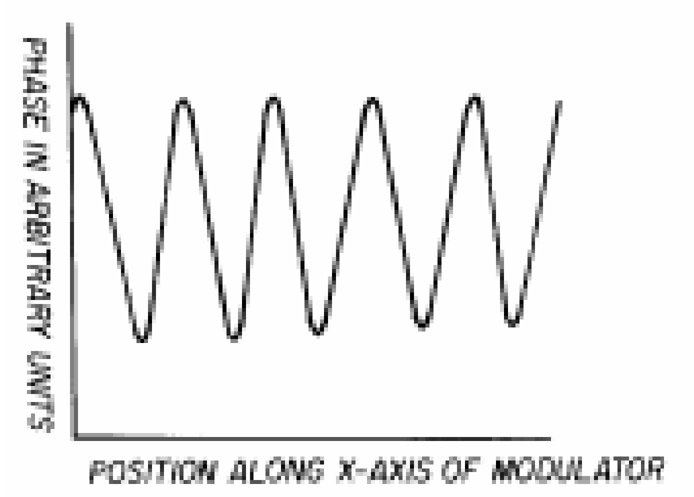
FIG. 2A

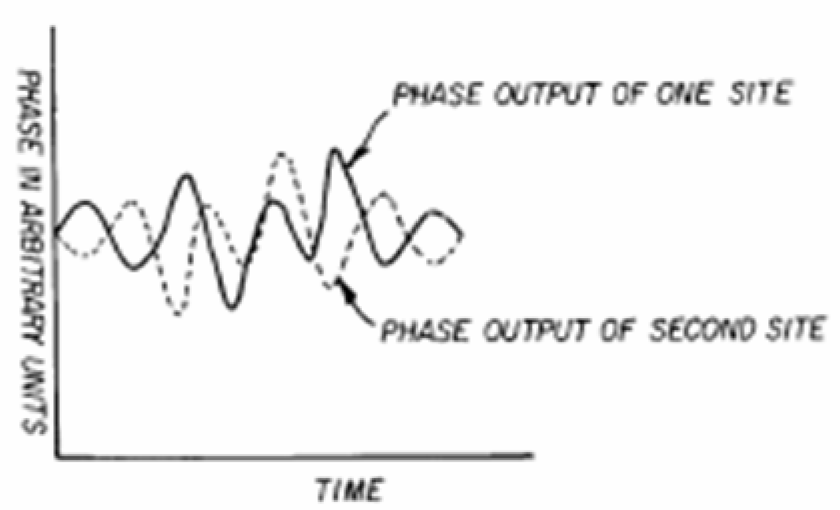


Speckle Reduction 10

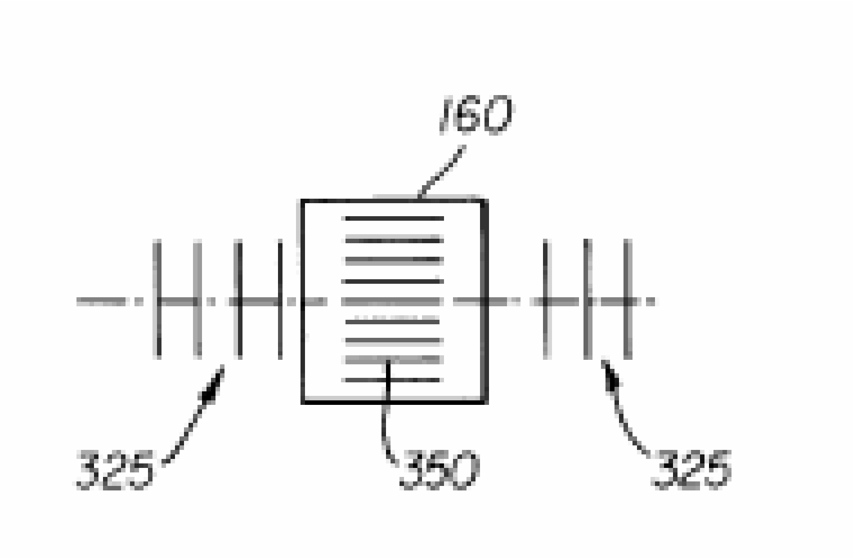


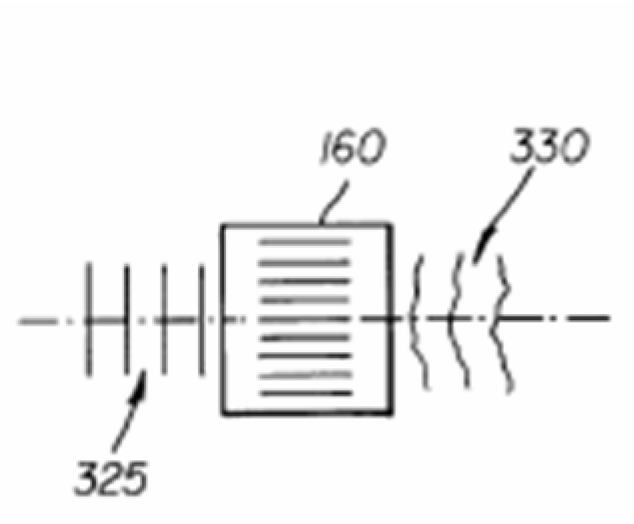


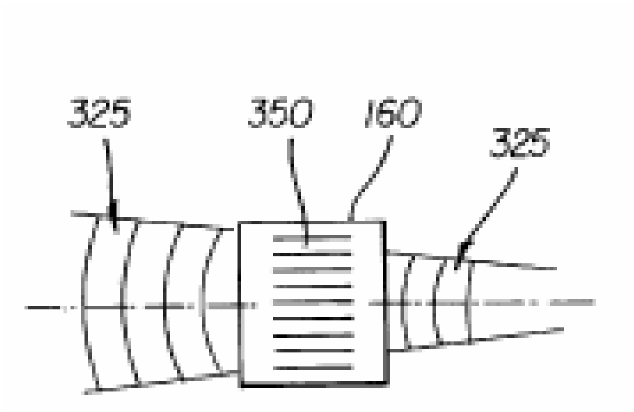


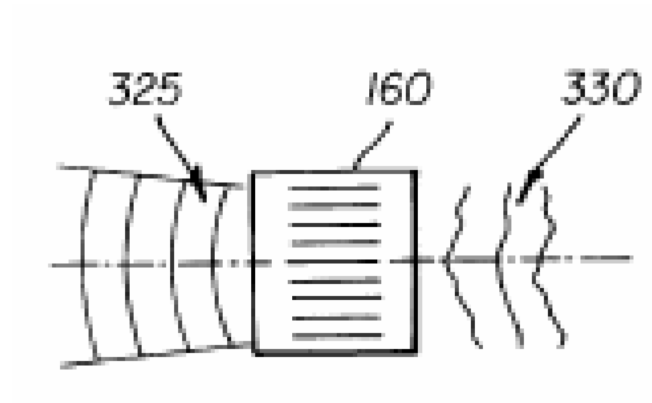


Speckle Reduction 10

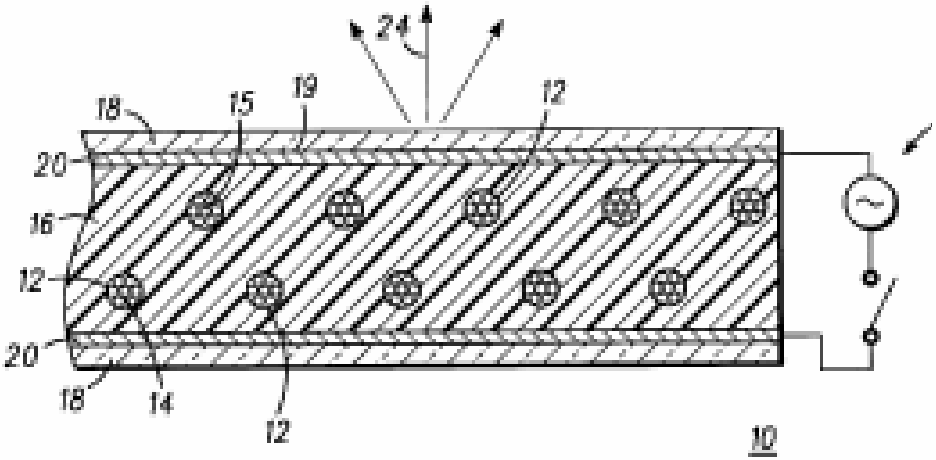


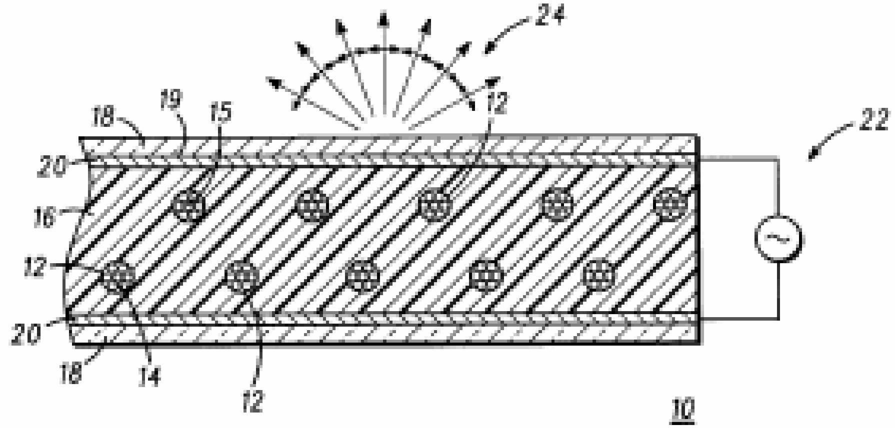






Motorola (US Patent 6,122,023)





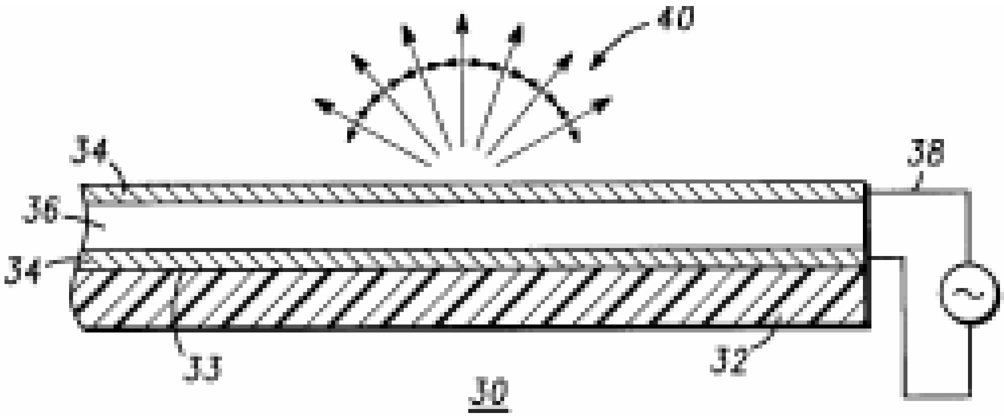
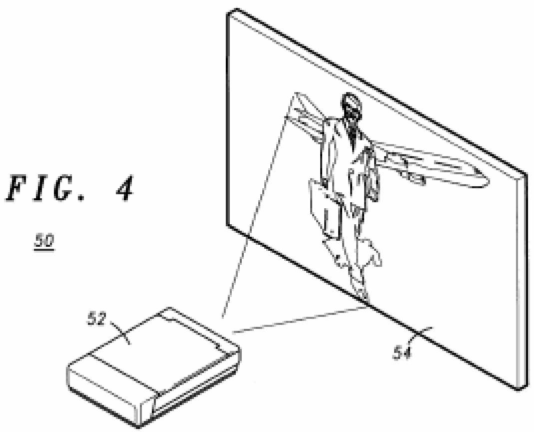


FIG. 4



Comparison

❑ Comparison of the speckle reducing methods

✓ Speckle contrast ratio

$$CR = \frac{\sqrt{\langle I_i^2 \rangle - \langle I_i \rangle^2}}{\langle I_i \rangle} = \frac{\sigma}{\mu}$$

where, $\langle I_i \rangle$: intensity of the i^{th} pixel of a CCD
σ : standard deviation, μ : mean value

– "Severe" speckle is associated with contrast measurement of CR > 0.30

– Comparison of spatial coherence degradation methods

Spatial coherence

Temporal coherence

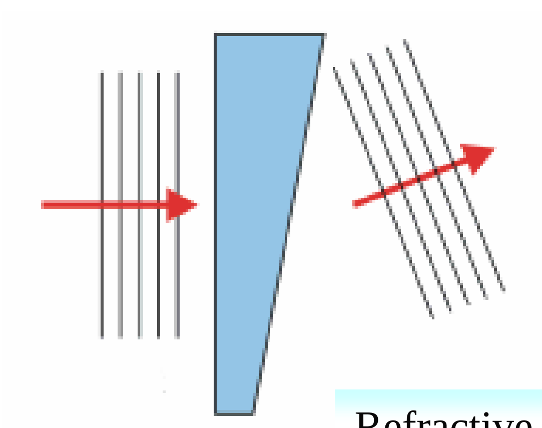
Component	Speckle contrast	Speckle reduction(%)	Insertion loss(%)
Stationary diffractive diffuser	**0.312**	**3.4**	**5**
Refractive lens array(6×8)	**0.309**	**4.3**	**14**
Fiber, 2m	**0.262**	**18.9**	**20**
Vibrated fiber	**0.057**	**82.4**	**20**
Vibrated diffractive diffuser	**0.048**	**85.1**	**5**
Vibrated projection screen	**0.034**	**89.5**	**0**
All vibrated components and lens arrays	**0.009**	**97.2**	**35**

LEOS '99, IEEE, pp.354-355.

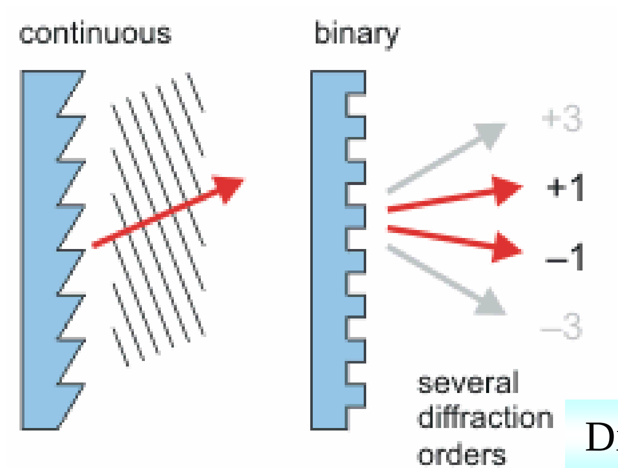
Diffractive Optical Elements

❑ Diffractive optical elements (DOEs)

- Operates on the principle of diffraction and interference
- Diffractive optics control wave fronts, while traditional optic components bend light.
- DOEs can function as gratings, lenses, and any other type of optical functional elements.
- Lightweight, thin and small, low-cost, and feasible for mass-production
- Wavelength-sensitive, chromatic aberration under white light



Refractive optics

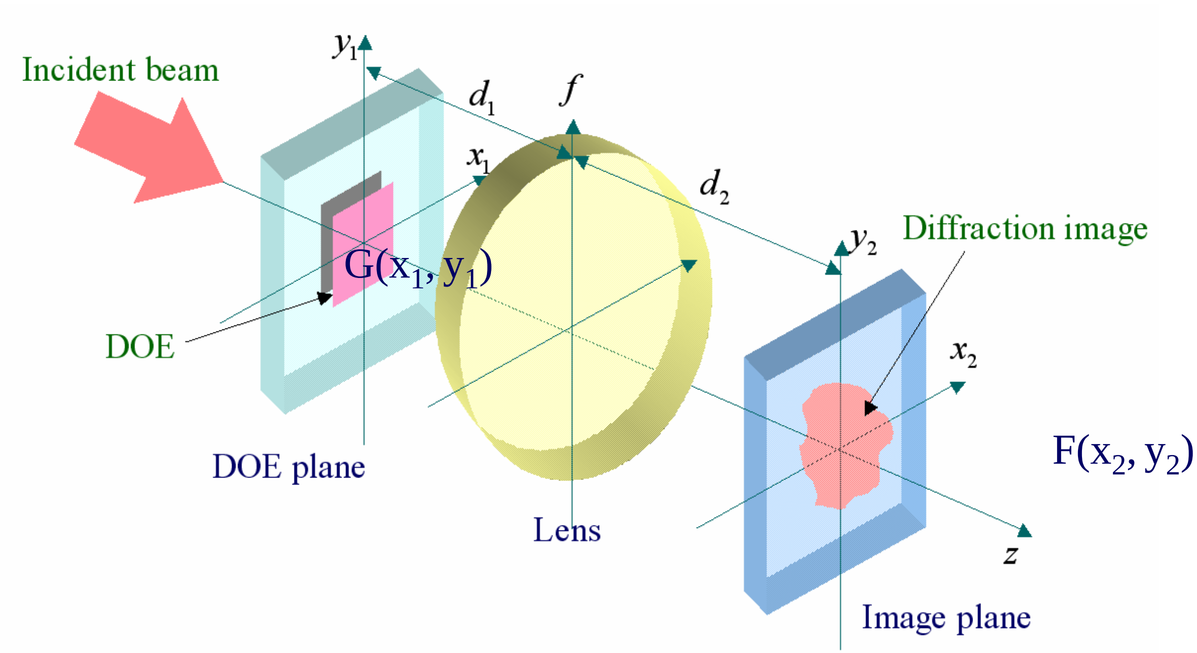


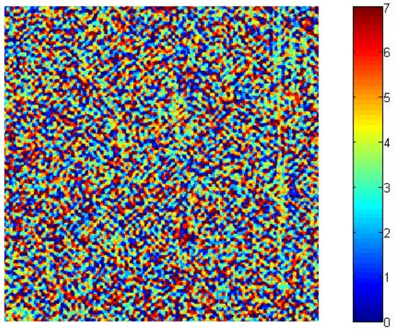
Diffractive optics

DOE Design 1

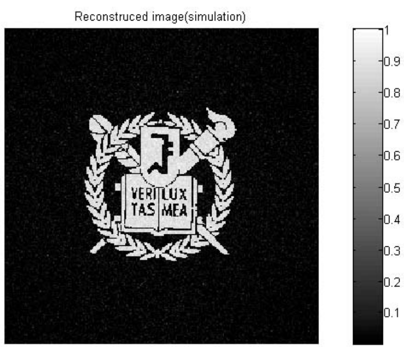
- **Generalized paraxial optical system**

$$F\left(x_2, y_2\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h\left(x_2, y_2, x_1, y_1\right) G\left(x_1, y_1\right) dx_1 dy_1 = Fr\left[G\left(x_1, y_1\right)\right]$$





Designed DOE



Reconstructed image

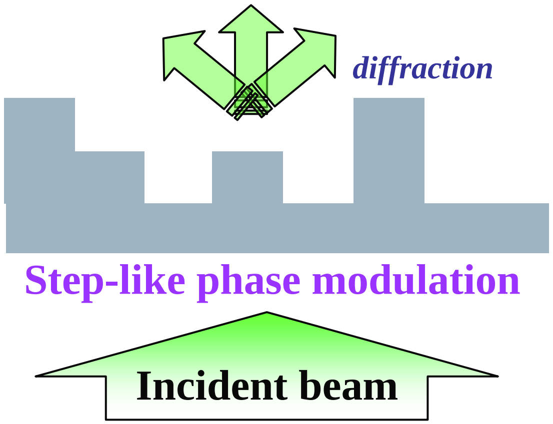
DOE Design 2

❑ Conventional Scalar based method

$$G(x_1, y_1) = A(x_1, y_1)\exp\left(i\Phi(x_1, y_1)\right)$$

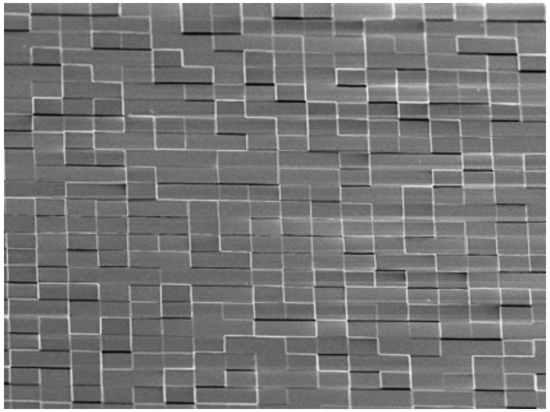
$A(x, y)$: amplitude of incident beam → fixed

$\Phi(x, y)$: phase distribution to be optimized



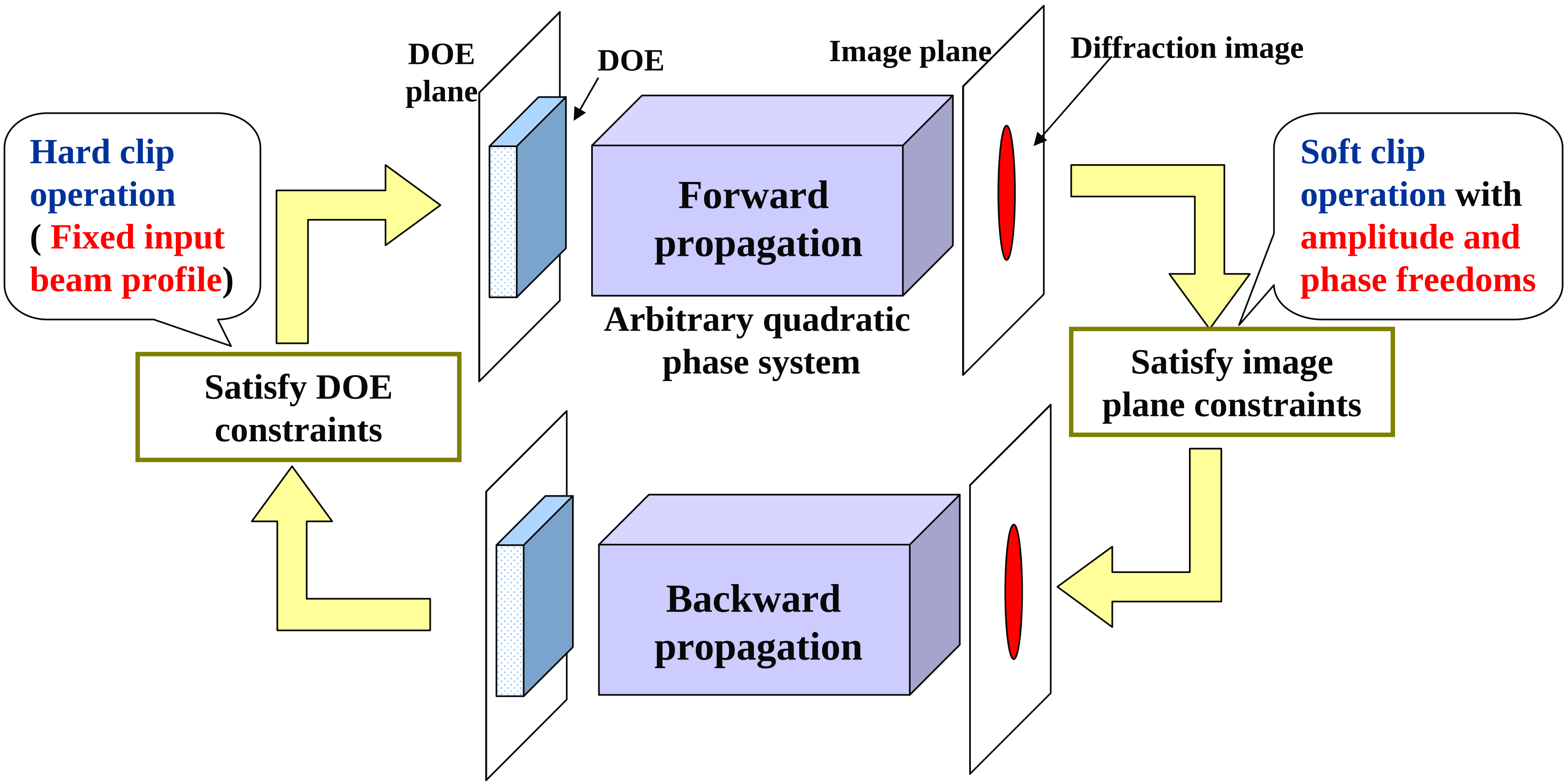
❑ Optimization methods (error-reduction)

- ✓ Local optimization
  - – Direct binary searching algorithm (DBS)
  - – Iterative Fourier transform algorithm (IFTA)
- ✓ Global optimization
  - – Simulated annealing method (SA)
  - – Genetic algorithm (GA)



Fabricated phase profiles (SEM image)

DOE Design 3

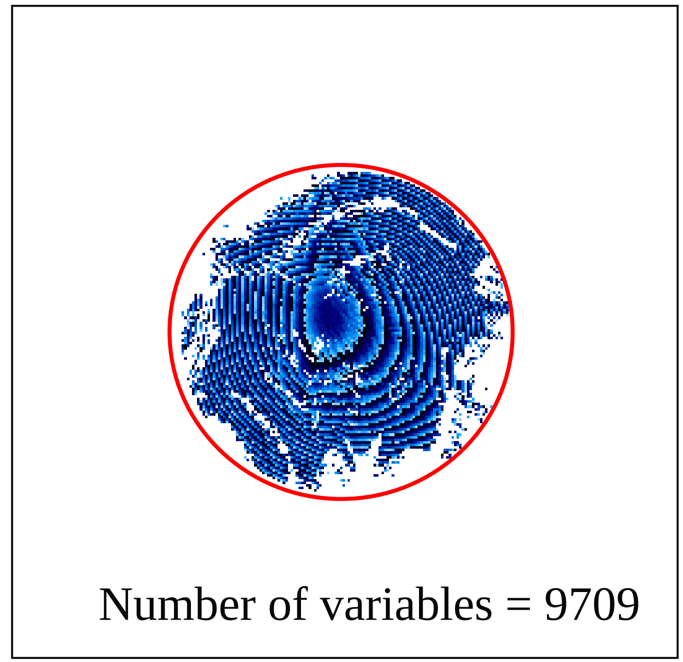


Hard clip operation (Fixed input beam profile)
Satisfy DOE constraints
DOE plane
DOE
Forward propagation
Arbitrary quadratic phase system
Image plane
Diffraction image
Soft clip operation with amplitude and phase freedoms
Satisfy image plane constraints
Backward propagation

Spiral Speckle and Boundary-Modulated DOE

Proposed design

Diffraction image

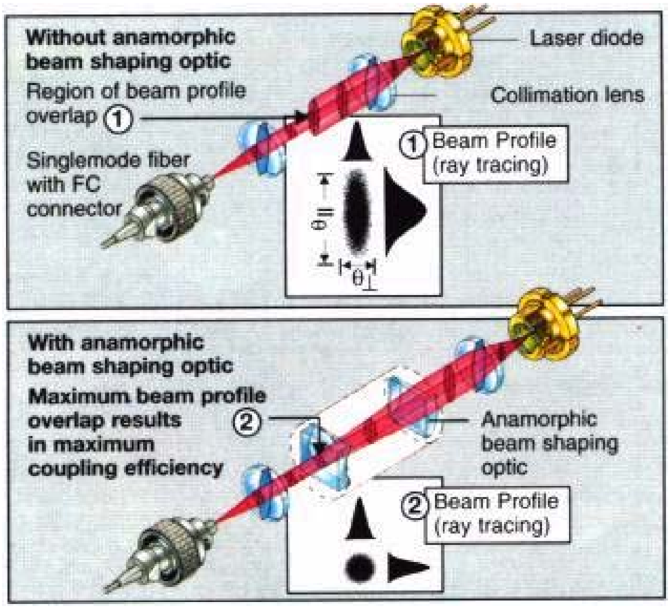


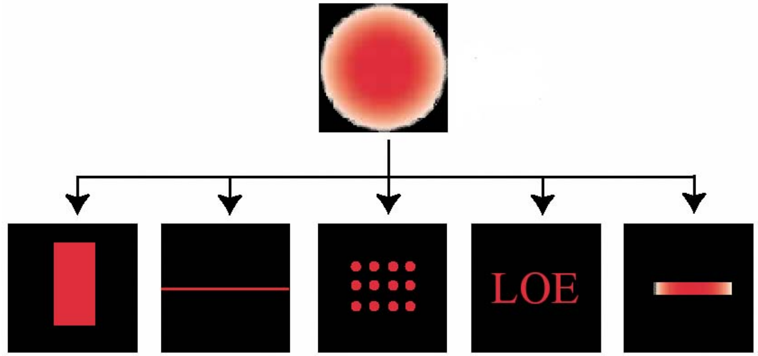
DOE profile

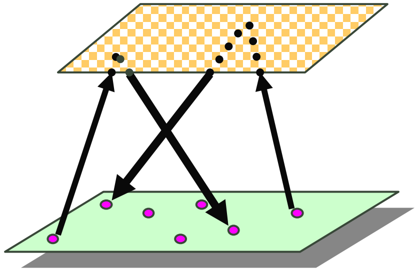
H. Kim and B. Lee, "Diffractive optical element with apodized aperture for shaping vortex-free diffraction image," Japanese Journal of Applied Physics, vol. 43, no. 12A, pp. L1530-L1533, 2004.

❑ DOE applications

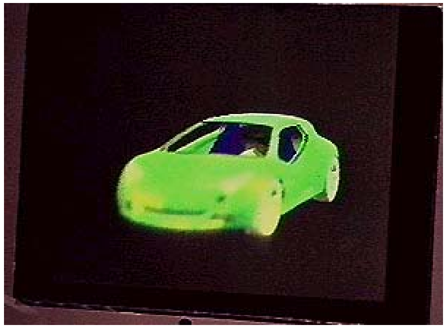
- ✓ Diffractive-refractive hybrid elements
- ✓ Beam shaping and pattern generation
- ✓ Optical interconnection
- ✓ 3D display







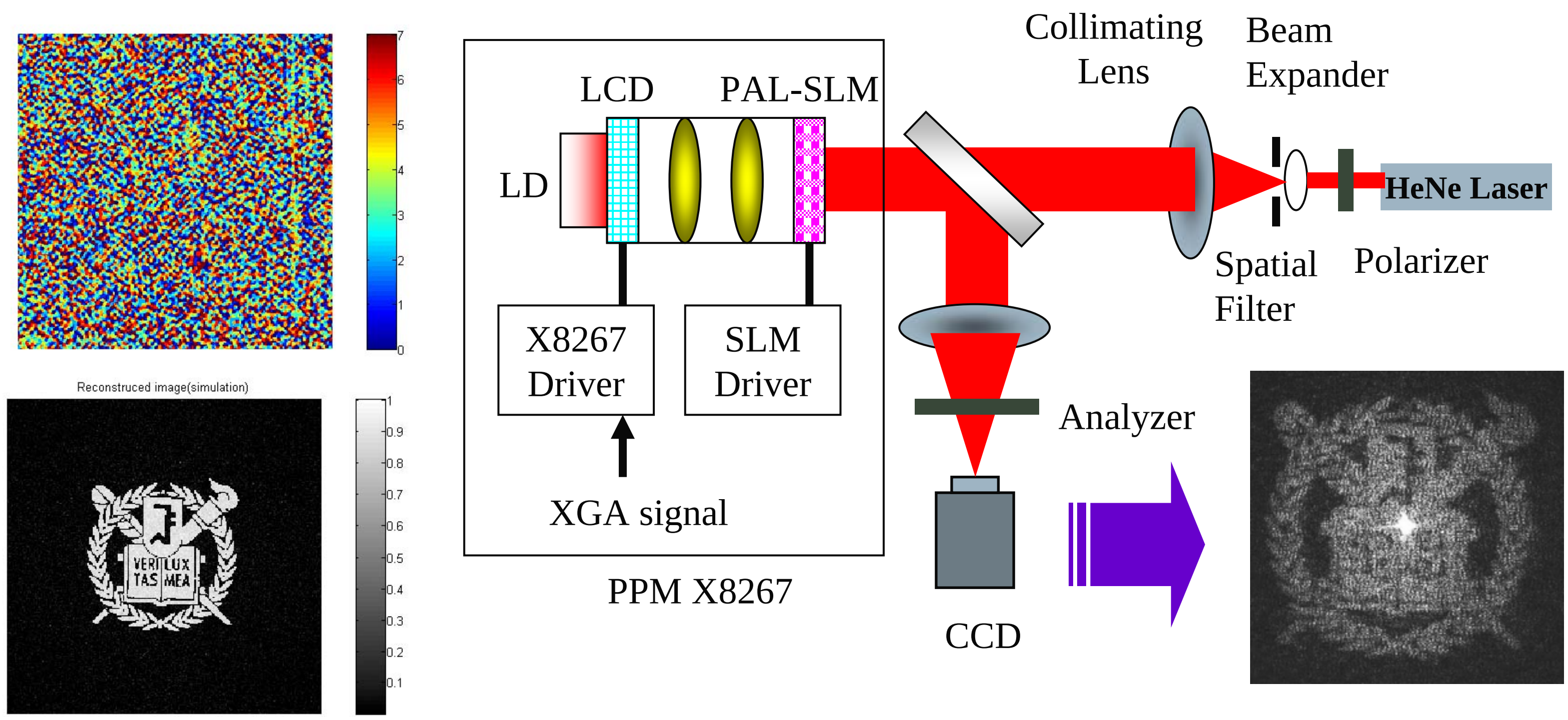
Intra-chip interconnection



❑ Experiment of DOE

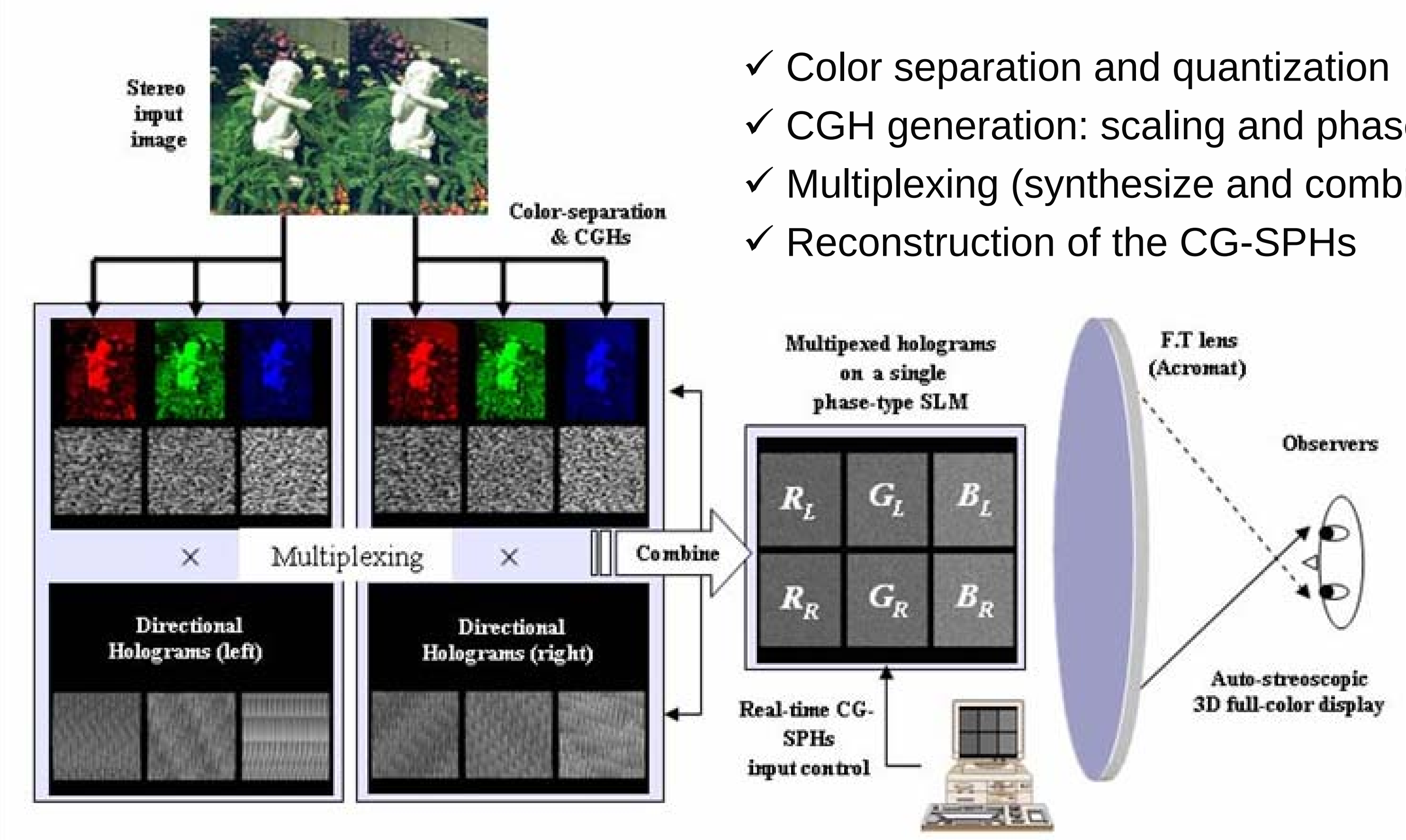
✓ Fourier optic system using SLM

– Phase-type spatial light modulator + designed phase DOE



Experimental setup using phase-type SLM

❑ Synthetic DOE (CGH)s for full-color display

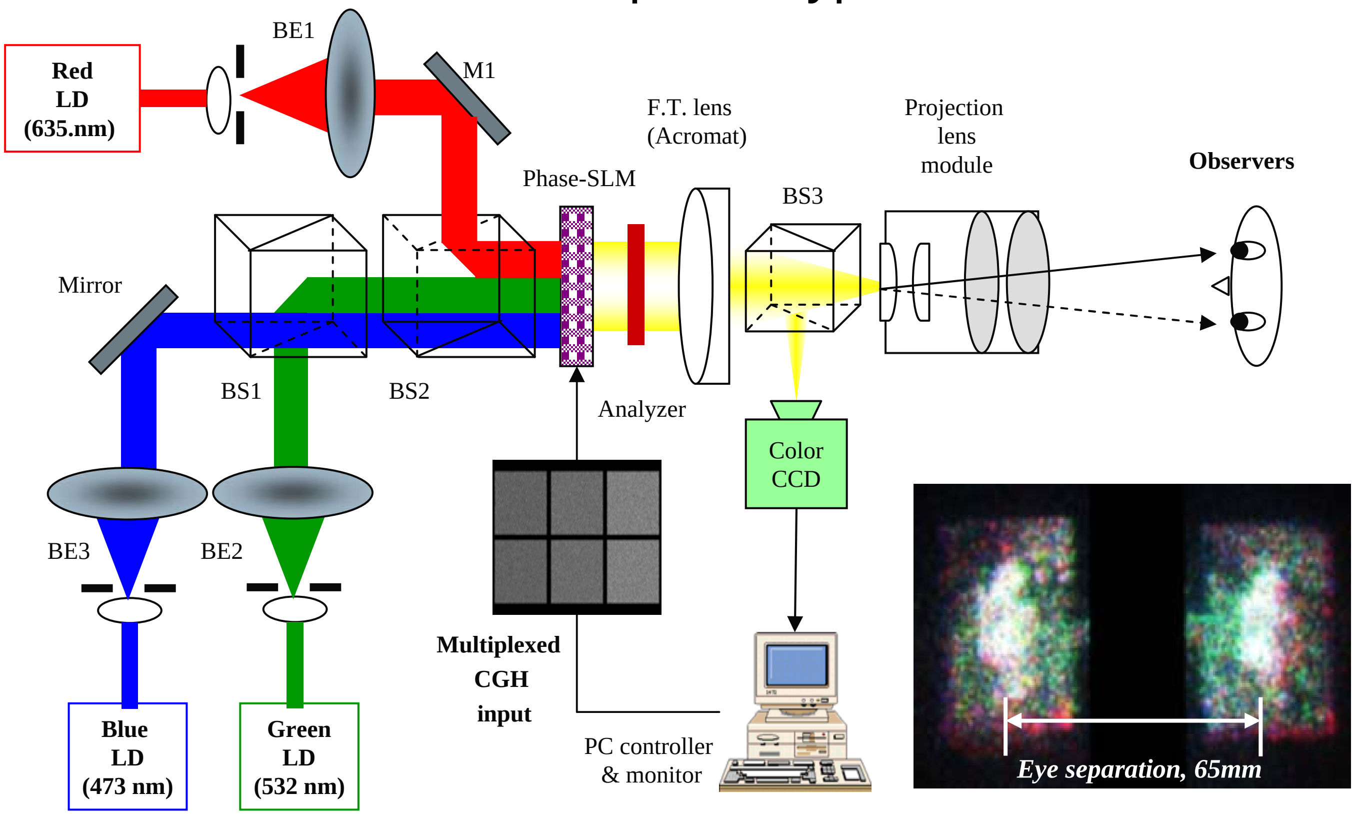


- ✓ Color separation and quantization
- ✓ CGH generation: scaling and phase leveling
- ✓ Multiplexing (synthesize and combine)
- ✓ Reconstruction of the CG-SPHs

Schematic diagram for full-color 3D image generation

❑ Full-color stereoscopic image display

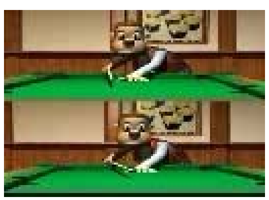
- ✓ Three color laser diodes and phase-type SLM



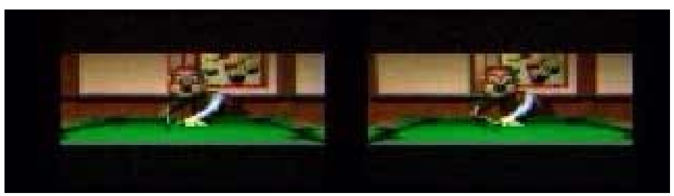
Experiment for full-color 3D image generation using phase-type SLM

❑ Full-color stereoscopic video display system

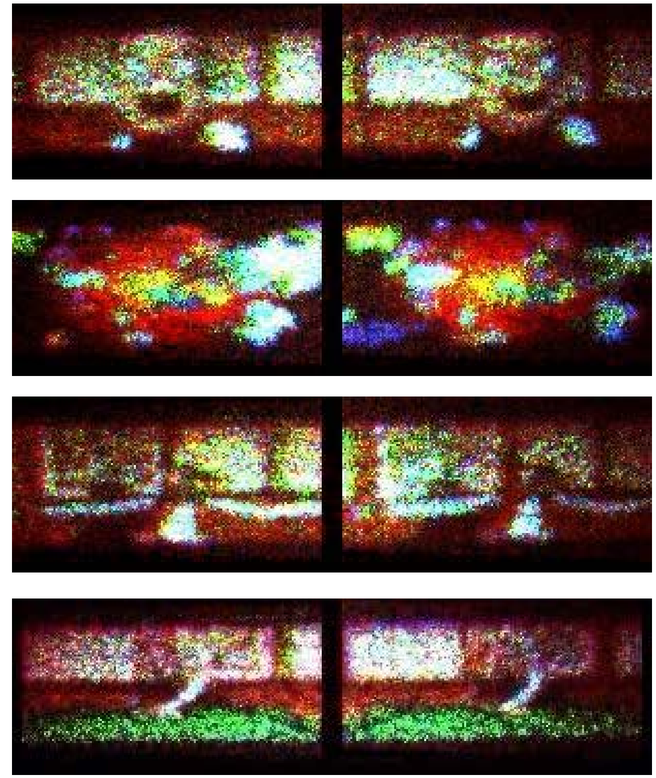
Full-color autostereoscopic 3D display demo system



Stereo input



Reconstructed stereo video (simulation)



Reconstructed stereo video (experiment)

Full-color stereoscopic video display demonstration sytem

Previous Work 1

❑ Fabrication process sequence

✓ Process sequence of DOE etching

– Glass substrate

– Glass cleaning

– HMDS (hexamethyldisilane 2%)+xylene

– PR coating

– Soft baking

– Photolithography exposure

– Develop

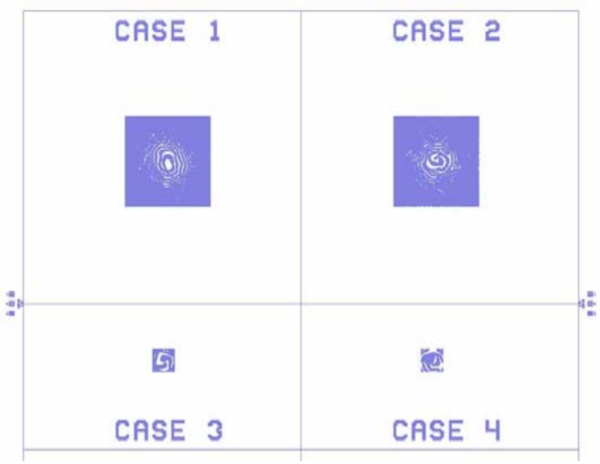
– Hard baking

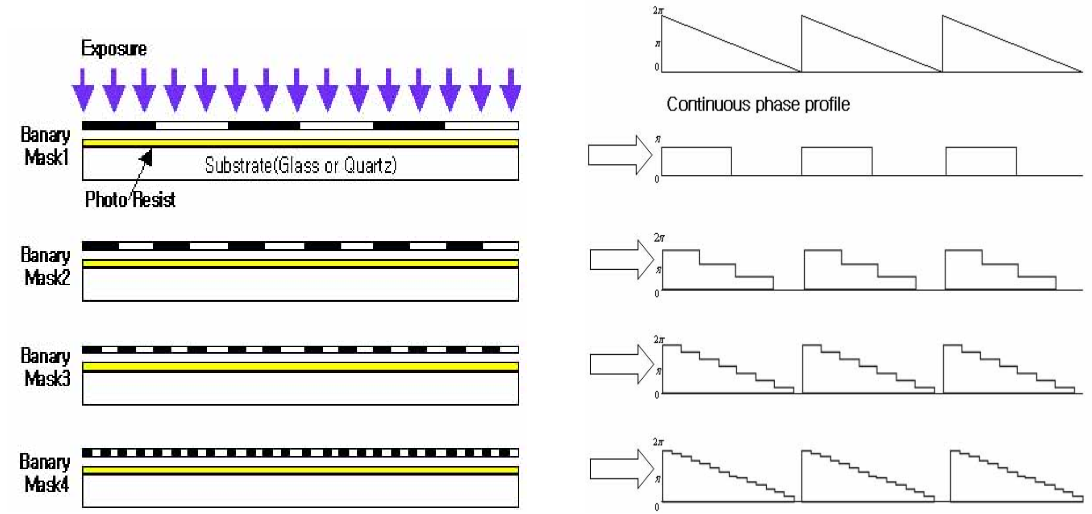
– Glass etching

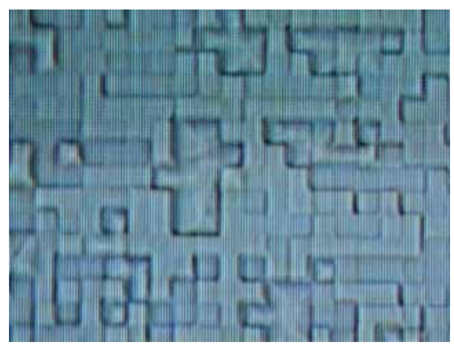
– PR stripe

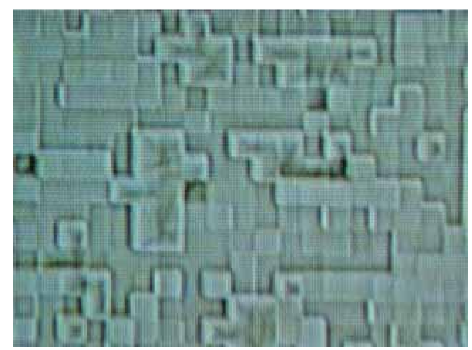
– Surface profile measurement

❑ Fabricated DOEs







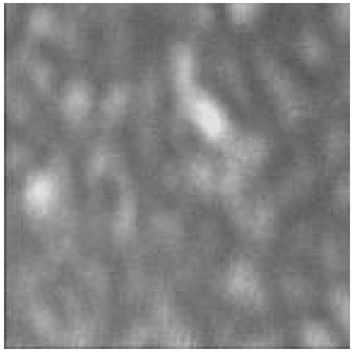


Microscope images with different focal length (height difference of the fabricated DOE)

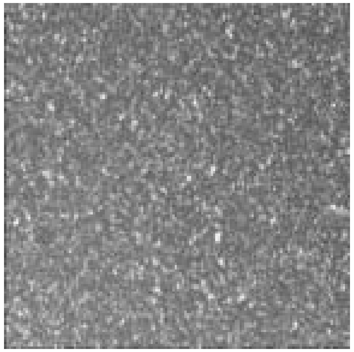
Previous Work 3

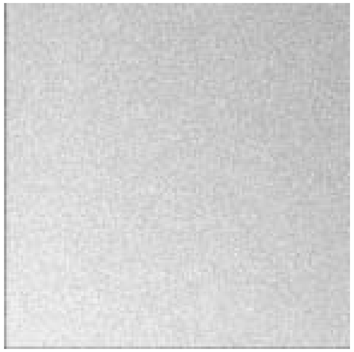
❑ Speckle intensity and histogram analysis

- ✓ Laser source (532nm DPSS Nd:YAG laser) + CCD



- ✓ DOE(16 level phase) & Rotated DOE at 5 rps





Conclusion

- **Introduction and overview on**
  - **- laser display systems**
  - **- speckle reduction methods**
  - **- DOE**