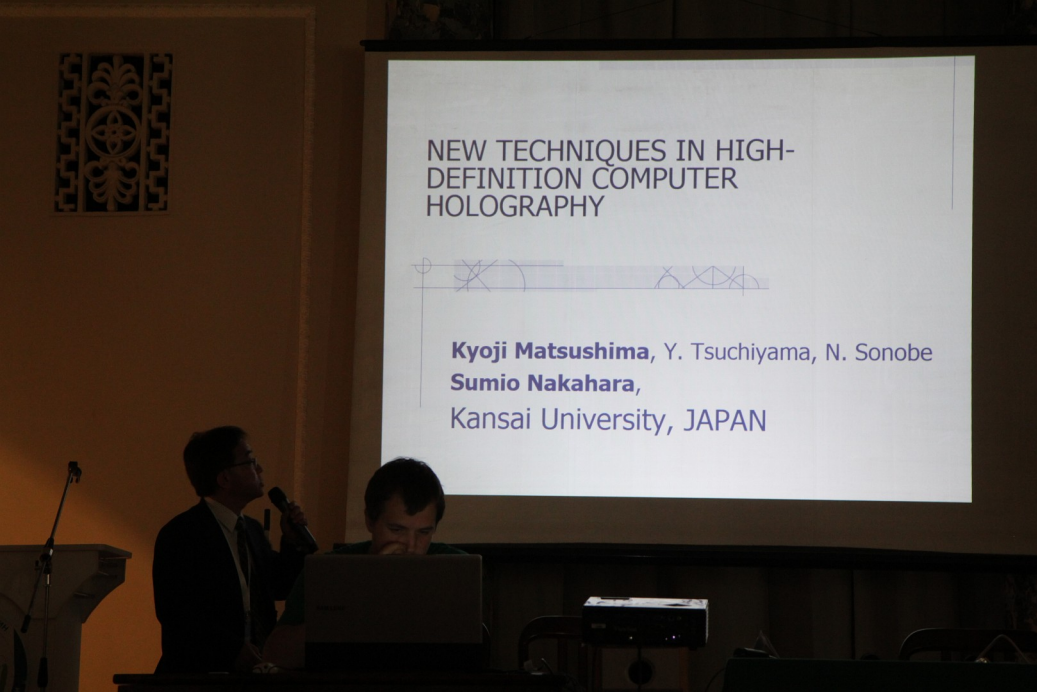
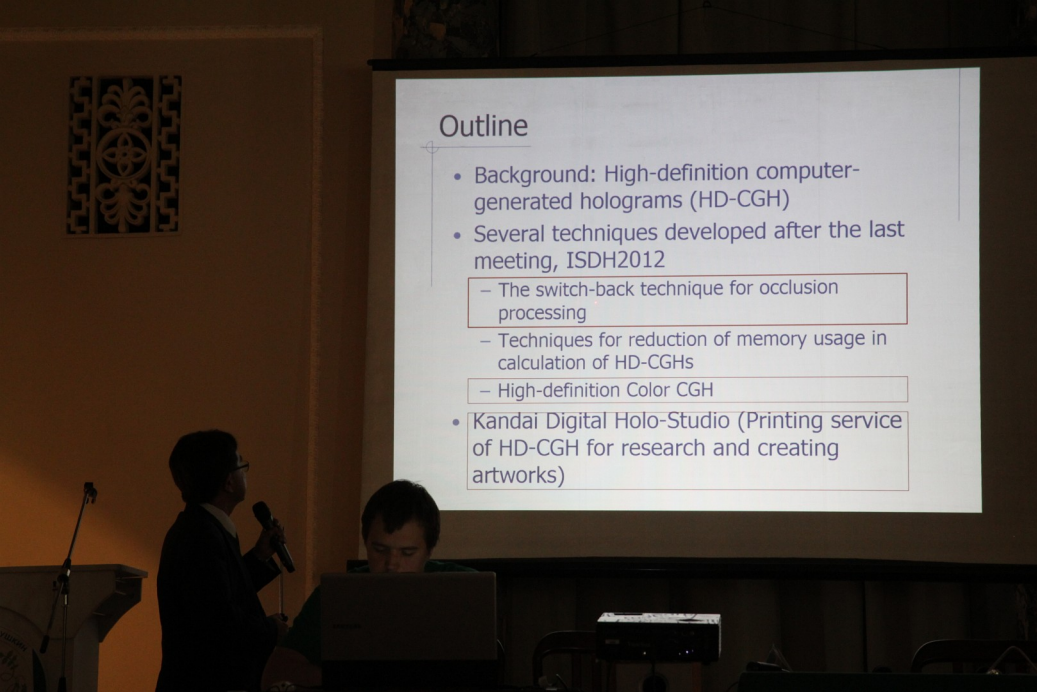
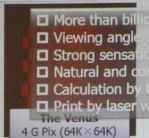

NEW TECHNIQUES IN HIGH-DEFINITION COMPUTER HOLOGRAPHY
Kyoji Matsushima, Y. Tsuchiyama, N. Sonobe
Sumio Nakahara,
Kansai University, JAPAN


Outline
• Background: High-definition computer-generated holograms (HD-CGH)
• Several techniques developed after the last meeting, ISDH2012
– The switch-back technique for occlusion processing
– Techniques for reduction of memory usage in calculation of HD-CGHs
– High-definition Color CGH
• Kandai Digital Holo-Studio (Printing service of HD-CGH for research and creating artworks)

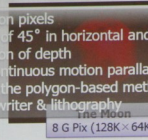
High-Definition Computer-Generated Holograms

- More than billion pixels
- Viewing angle of 45° in horizontal and vertical (full-parallax)
- Strong sensation of depth
- Natural and continuous motion parallax
- Calculation by the polygon-based method
- Print by laser writer & lithography



The Venus
4 G Pix (64K×64K)

K. Matsushima, S. Nakahara, Appl. Opt. **48**, H54-H63 (2009)



The Moon
8 G Pix (128K×64K)

K. Matsushima, H. Nishi, S. Nakahara, J. Electron. Imaging **21**, 023002 (2012)

The Metal Venus I
4 G Pix (64K×64K)

Nishi, K. Matsushima, S. Nakahara, Appl. Opt. **50**, H245-H252 (2011)

The Metal Venus II
G Pix (64K×64K)

K. Matsushima, S. Nakahara, **8281**, 828110 (2012)

Bear II
4 G Pix (64K×64K)

K. Matsushima, Y. Arima, S. Nakahara, Appl. Opt. **50**, H278-H284 (2011)

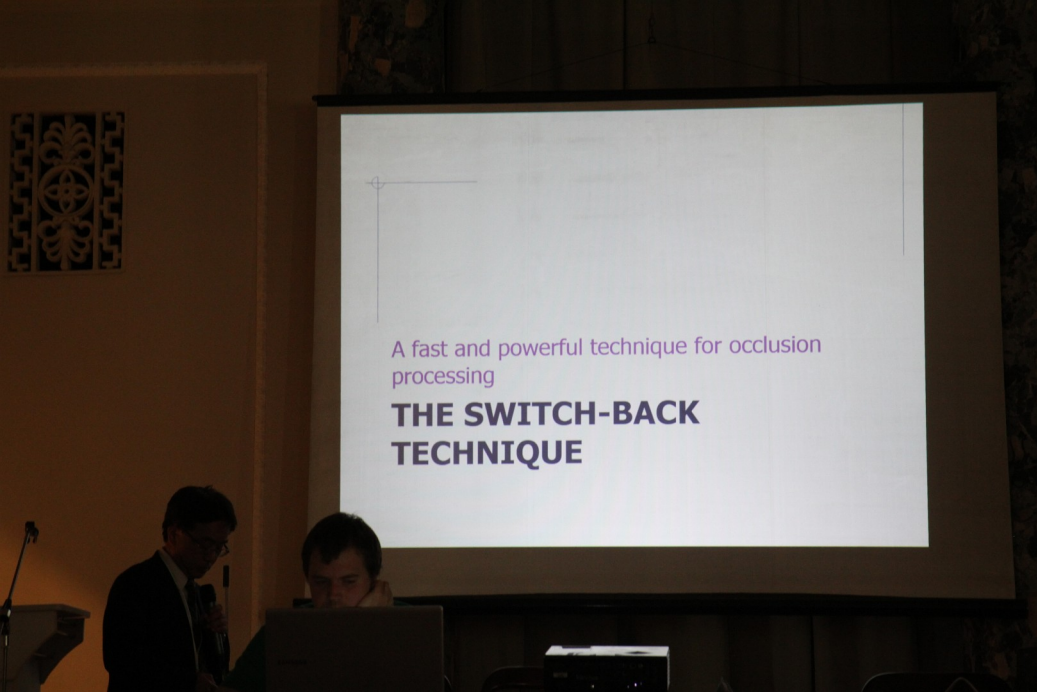
Five Ring
4 G Pix (64K×64K)

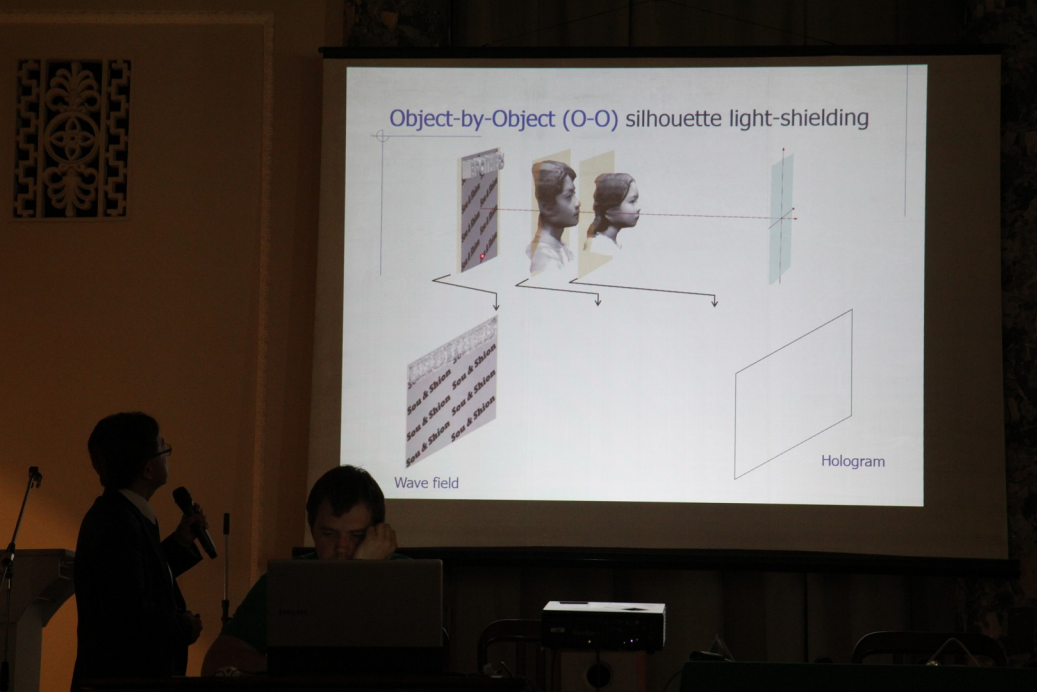
K. Matsushima, M. Nakamura, S. Nakahara, Opt. Express **22**, 24450 (2014)

Brothers exhibited in MIT museum

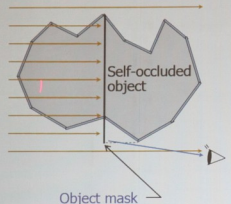
Brothers is on display at MIT museum up to March 2015 at least.

Brothers, 2012
25 G pix (196,608 × 131,072)


A fast and powerful technique for occlusion processing
THE SWITCH-BACK TECHNIQUE

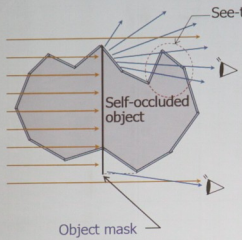

Object-by-Object (O-O) silhouette light-shielding
Wave field
Hologram

Drawback of object-by-object shielding



- If the object have self-occlusion, there may be see-through potion. In this case viewer may see partial phantom image.
- Object-by-object shielding cannot be applied to complicated-shape objects. This problem is resolved by shielding polygon-by-polygon.

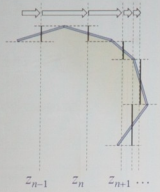
Drawback of object-by-object shielding



- If the object have self-occlusion, there may be see-through potion. In this case viewer may see partial phantom image.
- Object-by-object shielding cannot be applied to complicated-shape objects.
- This problem is resolved by shielding polygon-by-polygon.

Polygon-by-polygon (P-P) light-shielding

Propagation



$$u_{m+1}(x,y) = \mathbf{P}_{m+1,m}\{M_m(x,y)u_m(x,y) + O_m(x,y)\}$$

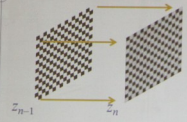
$A_{\text{silhouette}}$: Area of silhouette

A_{field}: Area of wave field

Filling ratio : $\dfrac{A_{\text{silhoutte}}}{A_{\text{field}}}$

Shielding unit	Number of masks	Size of silhouette (Filling ratio)	Distance between silhouettes
Object-by-object	1～10	Large (10～80%)	Long
Polygon-by-polygon	100～100,000	Very small (0.01～10%)	Short

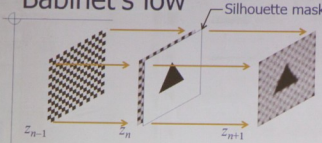
Babinet's low



Propagation $\times 2$

Propagation $\times 3$

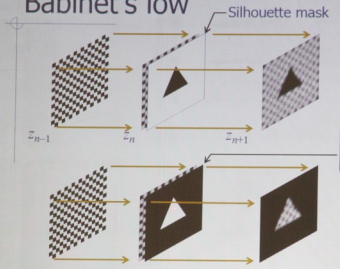
Babinet's low

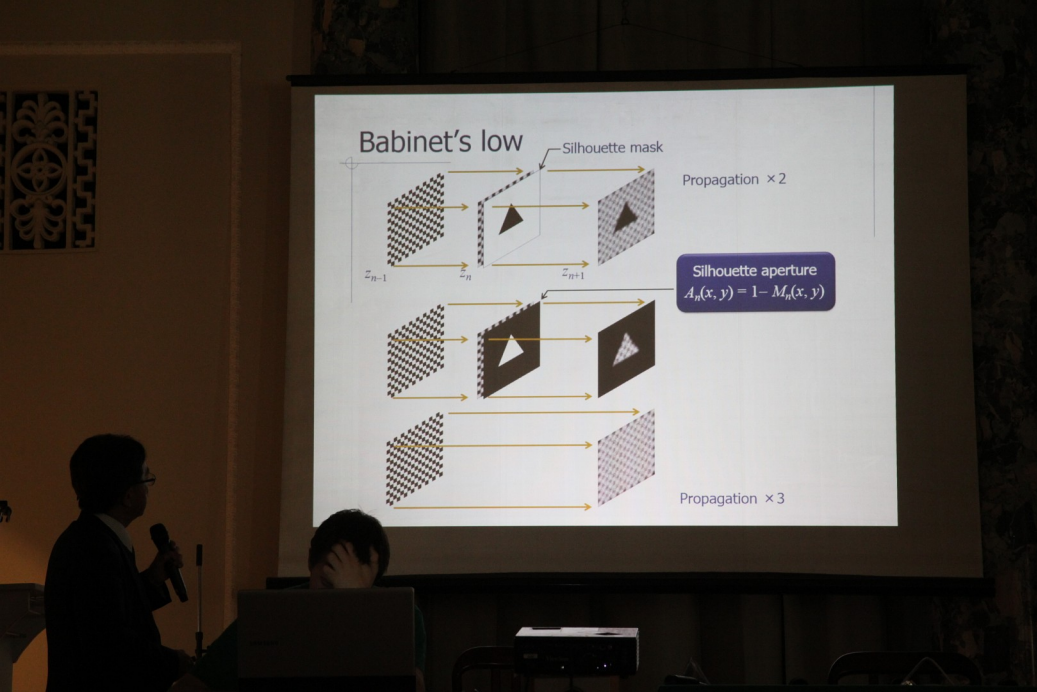


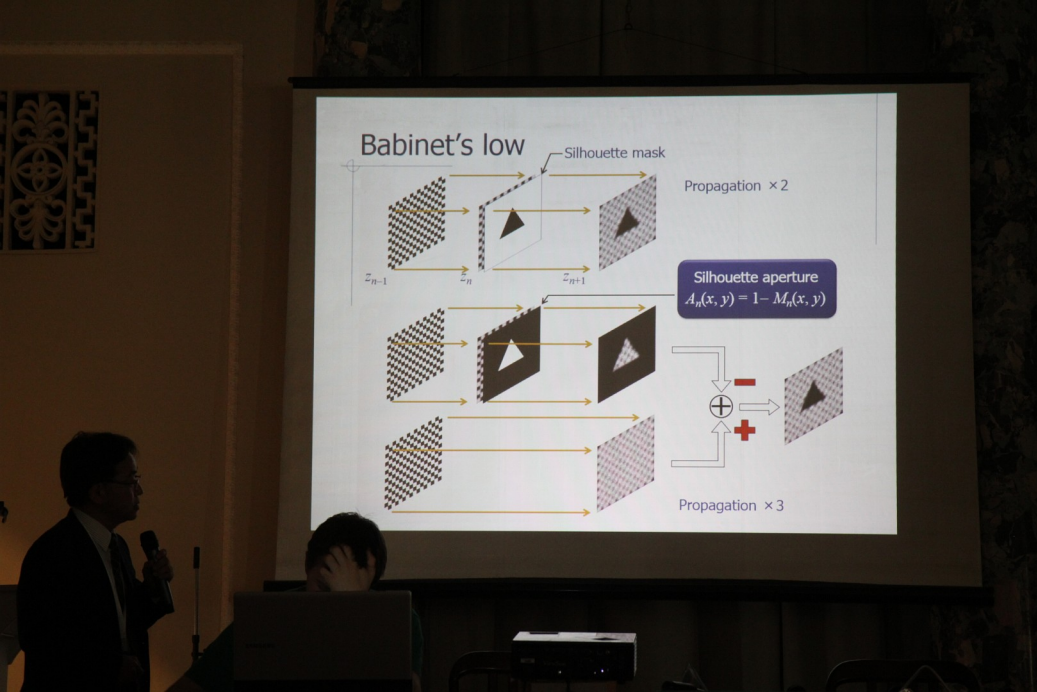
Propagation ×2

Propagation ×3

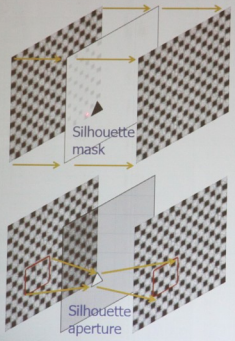
Babinet's low




Babinet's low
Silhouette mask
Propagation ×2
z_{n-1}
z_n
z_{n+1}
Silhouette aperture
$A_n(x, y) = 1 - M_n(x, y)$
Propagation ×3

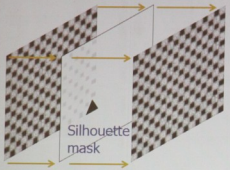

Babinet's low
Silhouette mask
Propagation ×2
z_{n-1}
z_n
z_{n+1}
Silhouette aperture
$A_n(x, y) = 1 - M_n(x, y)$
Propagation ×3

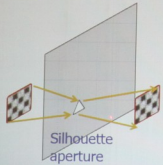
Advantage of silhouette aperture



- In silhouette-mask cases, the whole object field must be propagated to the next plane.
- In silhouette-aperture cases, only a small part of the field must be propagated to the next plane.
- Number of samplings can be reduced by using apertures instead of masks.

Advantage of silhouette aperture





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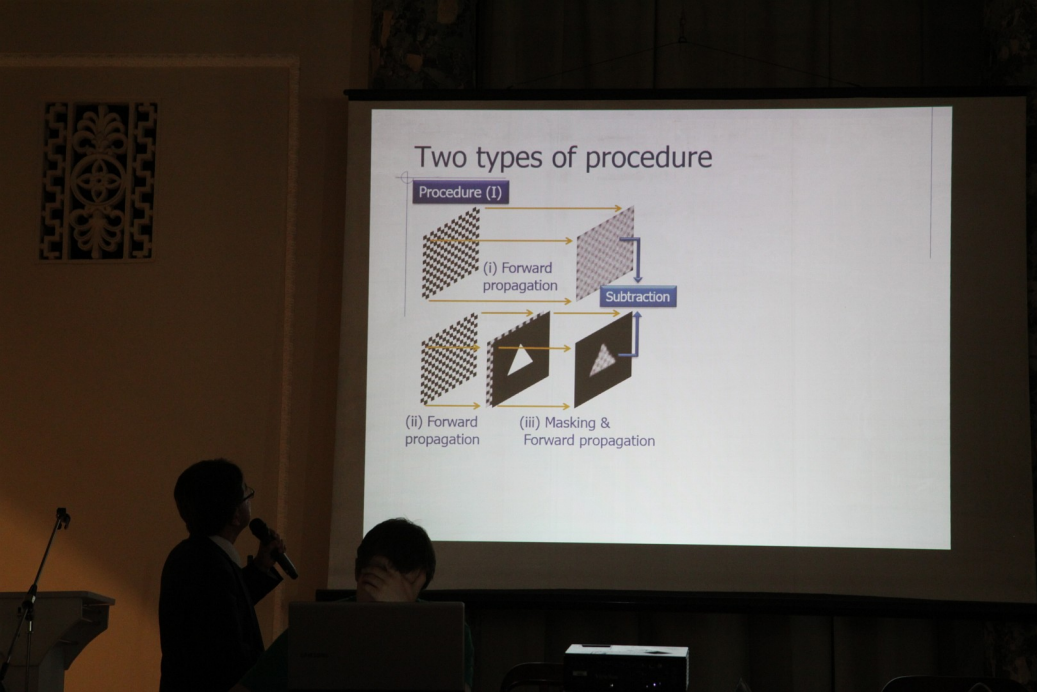
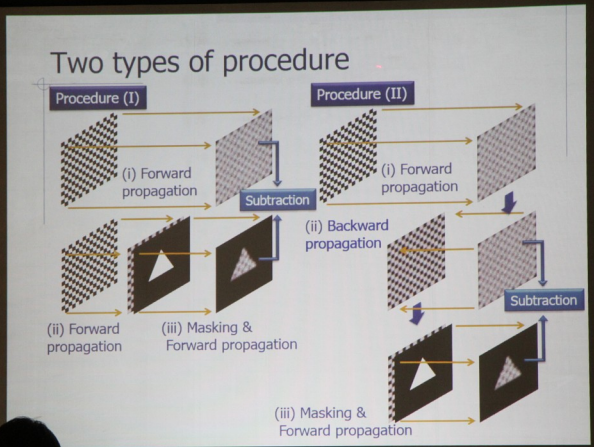

Two types of procedure
Procedure (I)
(i) Forward propagation
Subtraction
(ii) Forward propagation
(iii) Masking & Forward propagation


Two types of procedure
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(i) Forward propagation
(ii) Backward propagation
Subtraction
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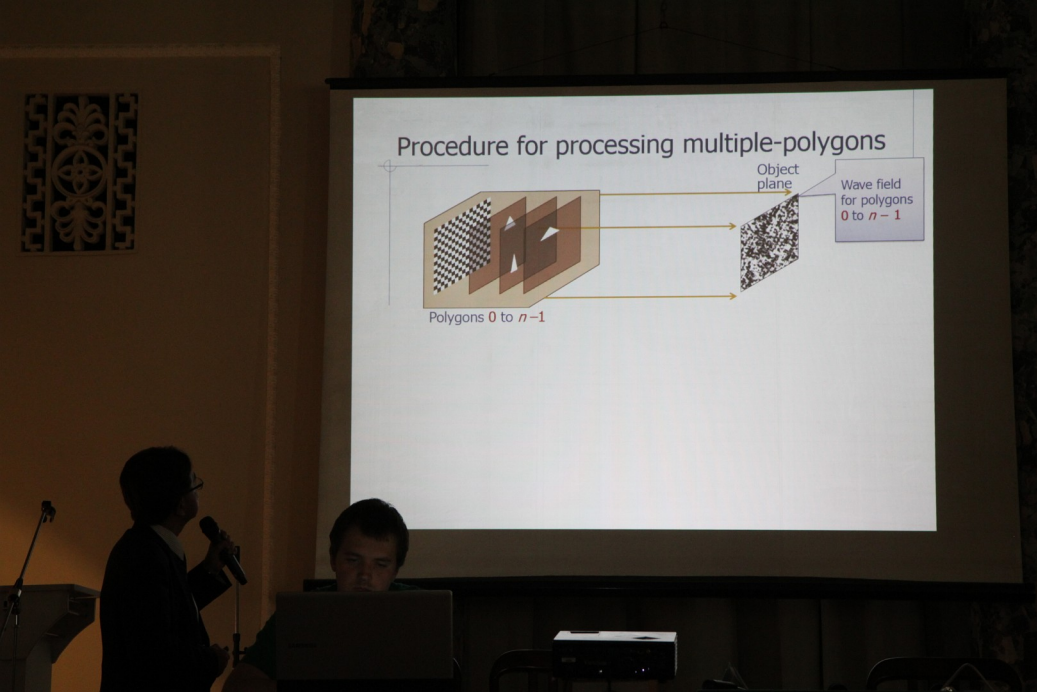
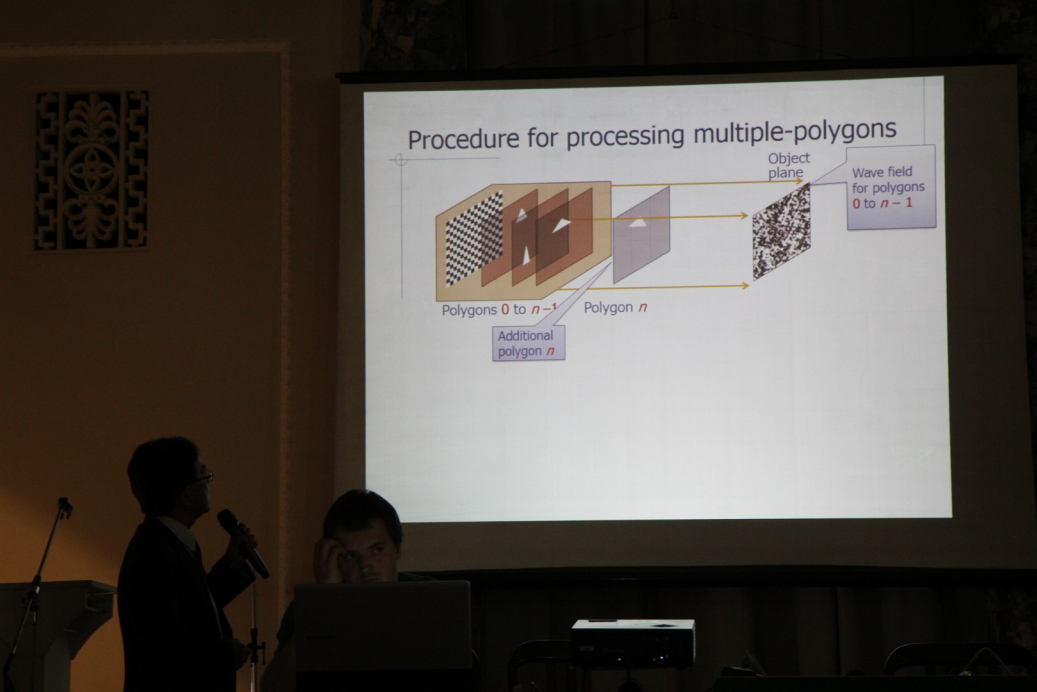
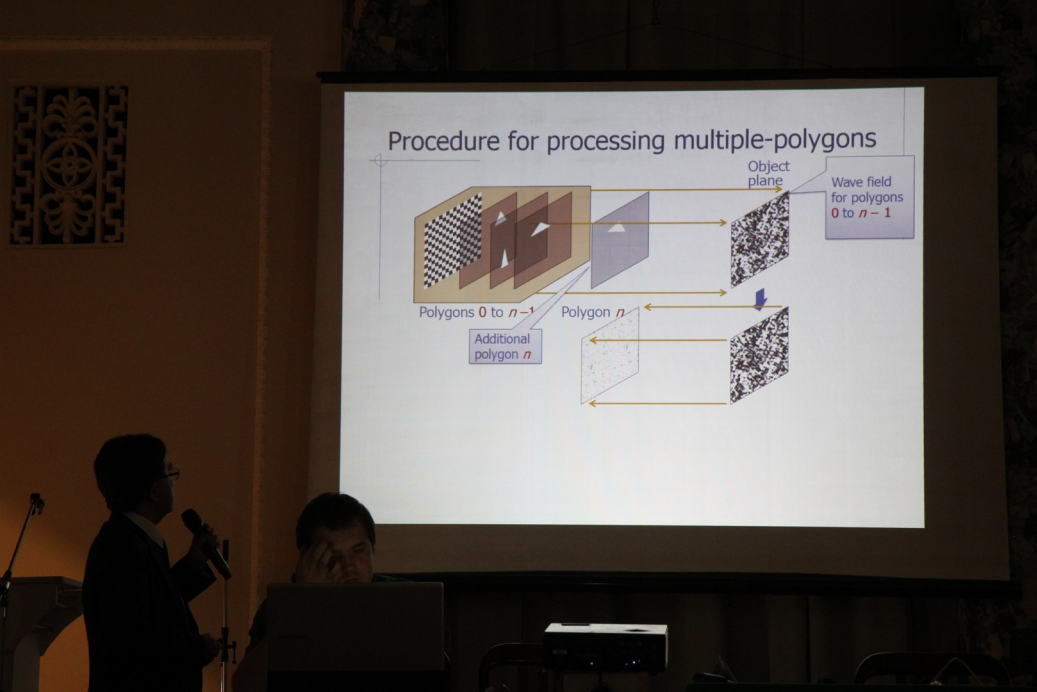
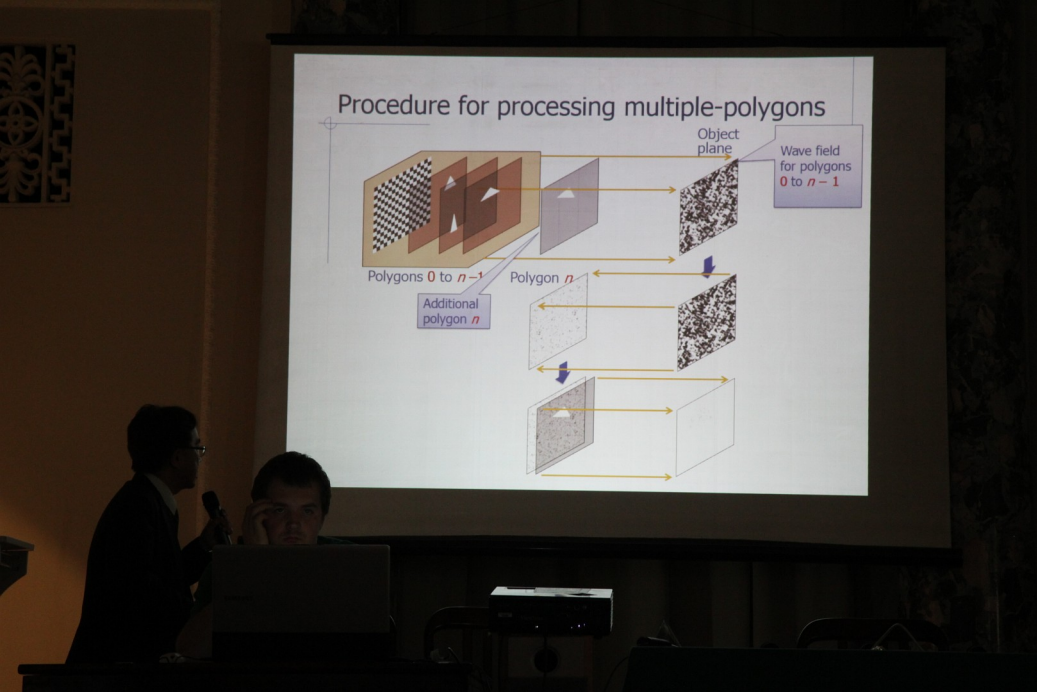

Procedure for processing multiple-polygons
Object plane
Wave field for polygons 0 to n − 1
Polygons 0 to n −1


Procedure for processing multiple-polygons
Object plane
Wave field for polygons 0 to n − 1
Polygons 0 to n −1
Polygon n
Additional polygon n


Procedure for processing multiple-polygons
Object plane
Wave field for polygons 0 to n − 1
Polygons 0 to n −1
Polygon n
Additional polygon n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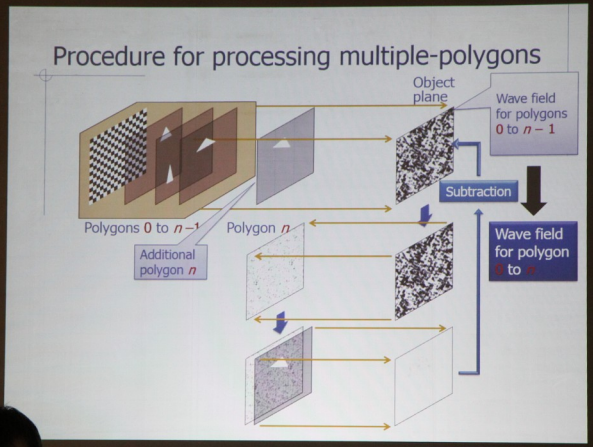
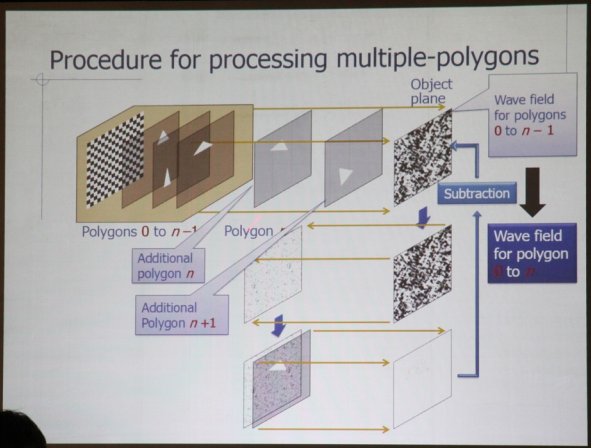
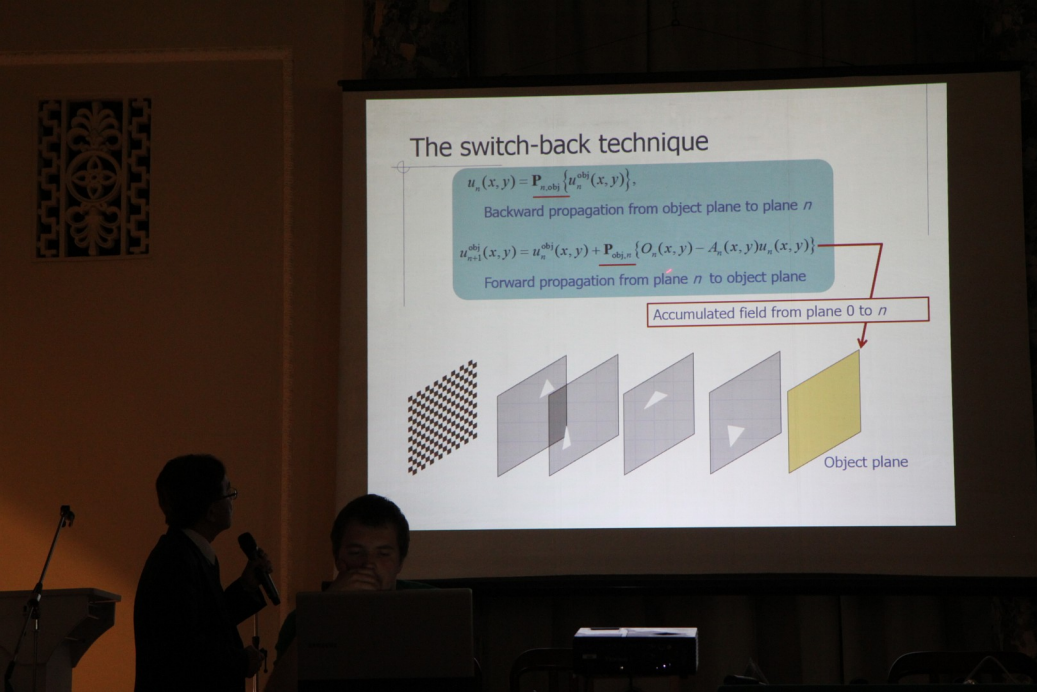
Polygons 0 to n −1
Polygon n
Additional polygon n


Procedure for processing multiple-polygons
Object plane
Wave field for polygons 0 to n − 1
Subtraction
Polygons 0 to n −1
Polygon n
Additional polygon n
Wave field for polygon 0 to n


Procedure for processing multiple-polygons
Object plane
Wave field for polygons 0 to n – 1
Subtraction
Wave field for polygon 0 to n
Polygons 0 to n –1
Polygon n
Additional polygon n
Additional Polygon n +1


The switch-back technique
$u_n(x,y) = \mathbf{P}_{n,\mathrm{obj}}\{u_n^{\mathrm{obj}}(x,y)\}$,
Backward propagation from object plane to plane n
$u_{n+1}^{\mathrm{obj}}(x,y) = u_n^{\mathrm{obj}}(x,y) + \mathbf{P}_{\mathrm{obj},n}\{O_n(x,y) - A_n(x,y)u_n(x,y)\}$
Forward propagation from plane n to object plane
Accumulated field from plane 0 to n
Object plane

The switch-back technique

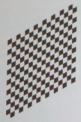
$$u_n(x,y) = \mathbf{P}_{n,\mathrm{obj}}\left\{u_n^{\mathrm{obj}}(x,y)\right\},$$

Backward propagation from object plane to plane n

$$u_{n+1}^{\mathrm{obj}}(x,y) = u_n^{\mathrm{obj}}(x,y) + \mathbf{P}_{\mathrm{obj},n}\left\{O_n(x,y) - A_n(x,y)u_n(x,y)\right\}$$

Forward propagation from plane n to object plane

Accumulated field from plane 0 to n



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Forward propagation from plane n to object plane

Accumulated field from plane 0 to n

The switch-back technique

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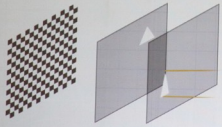
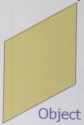
Forward propagation from plane n to object plane

Accumulated field from plane 0 to n





Object plane

The switch-back technique

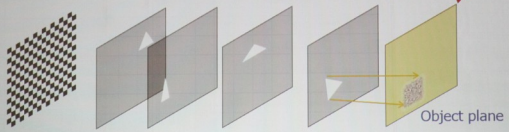
$$u_n(x,y) = \mathbf{P}_{n,\mathrm{obj}}\left\{u_n^{\mathrm{obj}}(x,y)\right\},$$

Backward propagation from object plane to plane n

$$u_{n+1}^{\mathrm{obj}}(x,y) = u_n^{\mathrm{obj}}(x,y) + \mathbf{P}_{\mathrm{obj},n}\left\{O_n(x,y) - A_n(x,y)u_n(x,y)\right\}$$

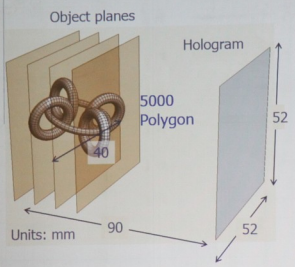
Forward propagation from plane n to object plane

Accumulated field from plane 0 to n



The procedure is called switch-back technique, because field is propagated back and forth.

Measurement of performance



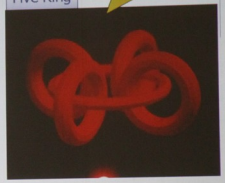
Indicated sizes are of the full-size model.

Pixel pitch: 0.8 μm × 0.8 μm
Wavelength: 633 nm

1K = 1024

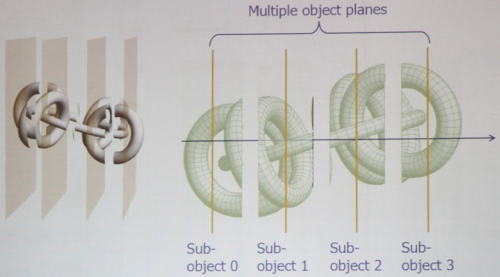
This CGH is on display in the back of this room

Five Ring



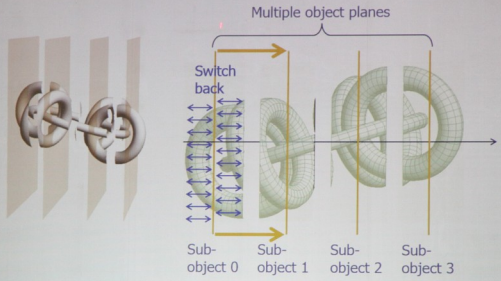
Model	No. of pixels
Full-size	$64K \times 64K$ (4.3×10^9)
1/32 scale	$2K \times 2K$ (4.2×10^6)

Speedup by splitting object



- Switch back technique works better when the object depth is smaller, because polygons are located close to the object plane.
- Splitting the object definitely reduce the computation time.

Speedup by splitting object



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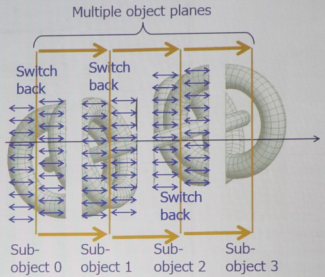

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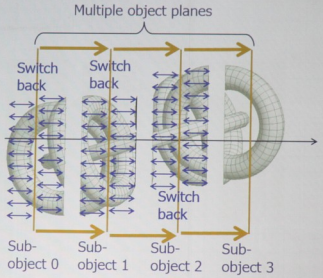

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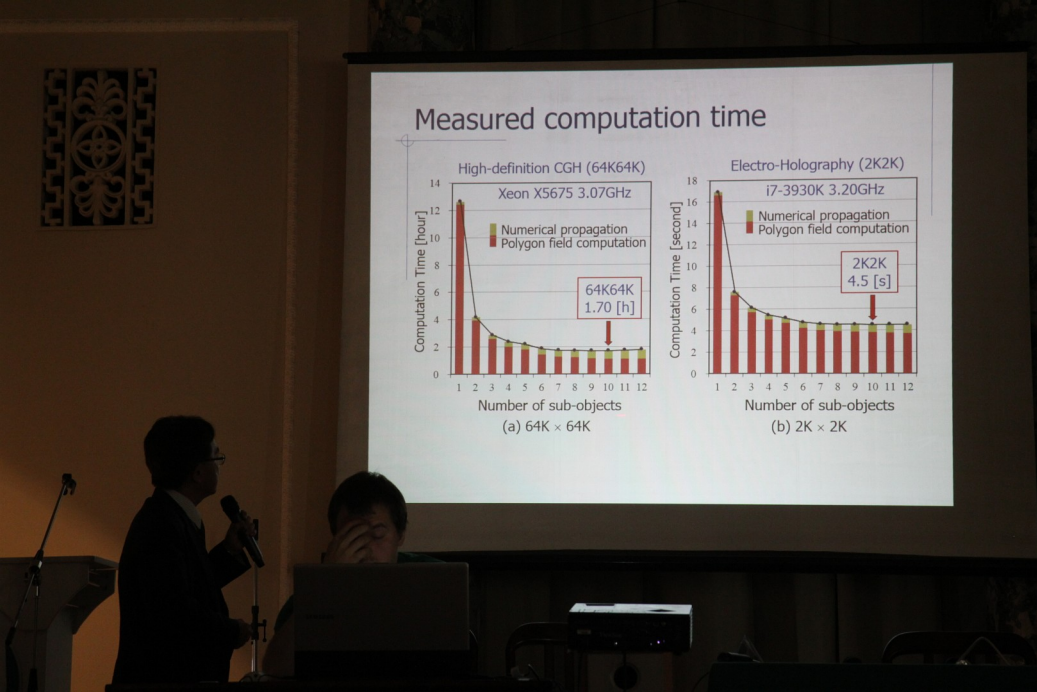
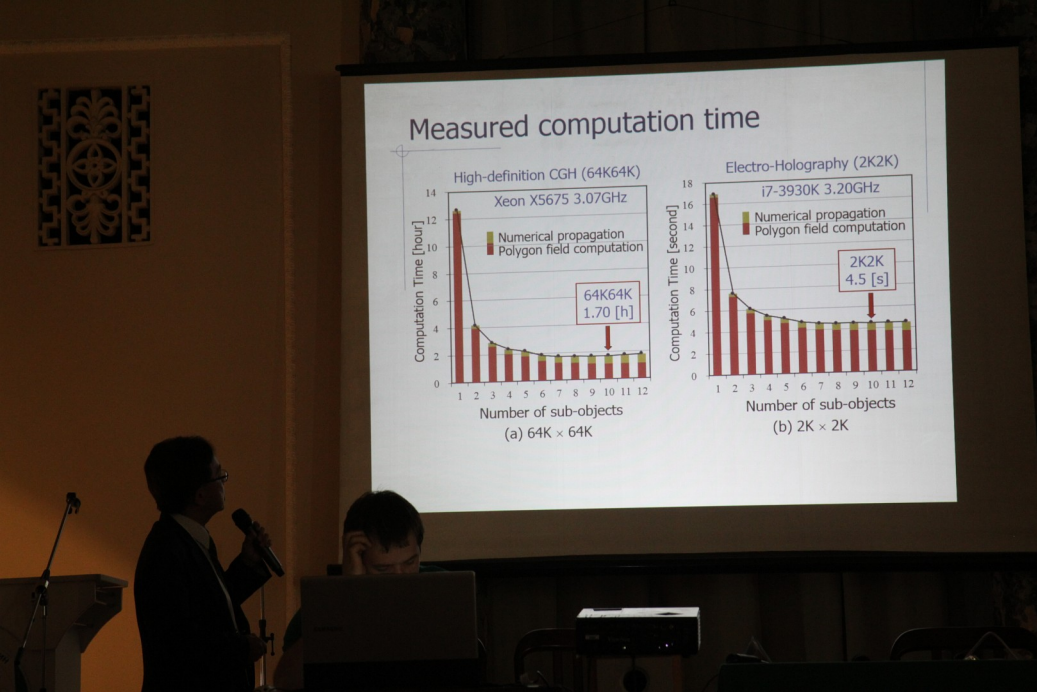

Measured computation time
High-definition CGH (64K64K)
Xeon X5675 3.07GHz
Numerical propagation
Polygon field computation
64K64K
1.70 [h]
Computation Time [hour]
Number of sub-objects
(a) 64K × 64K
Electro-Holography (2K2K)
i7-3930K 3.20GHz
Numerical propagation
Polygon field computation
2K2K
4.5 [s]
Computation Time [second]
Number of sub-objects
(b) 2K × 2K


Measured computation time
High-definition CGH (64K64K)
Xeon X5675 3.07GHz
Numerical propagation
Polygon field computation
64K64K
1.70 [h]
Computation Time [hour]
Number of sub-objects
(a) 64K × 64K
Electro-Holography (2K2K)
i7-3930K 3.20GHz
Numerical propagation
Polygon field computation
2K2K
4.5 [s]
Computation Time [second]
Number of sub-objects
(b) 2K × 2K

Simple transformation of CG model to CGH by Switch-Back technique

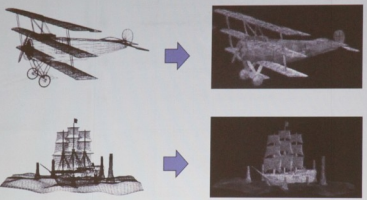
CG model

CGH reconstruction

- Switch back technique make it possible to compute the field of very complex models and simply convert the model to CGH.

K. Matsushima, M. Nakamura, S. Nakahara, Opt. Express **22**, 24450 (2014)

Simple transformation of CG model to CGH by Switch-Back technique



CG model

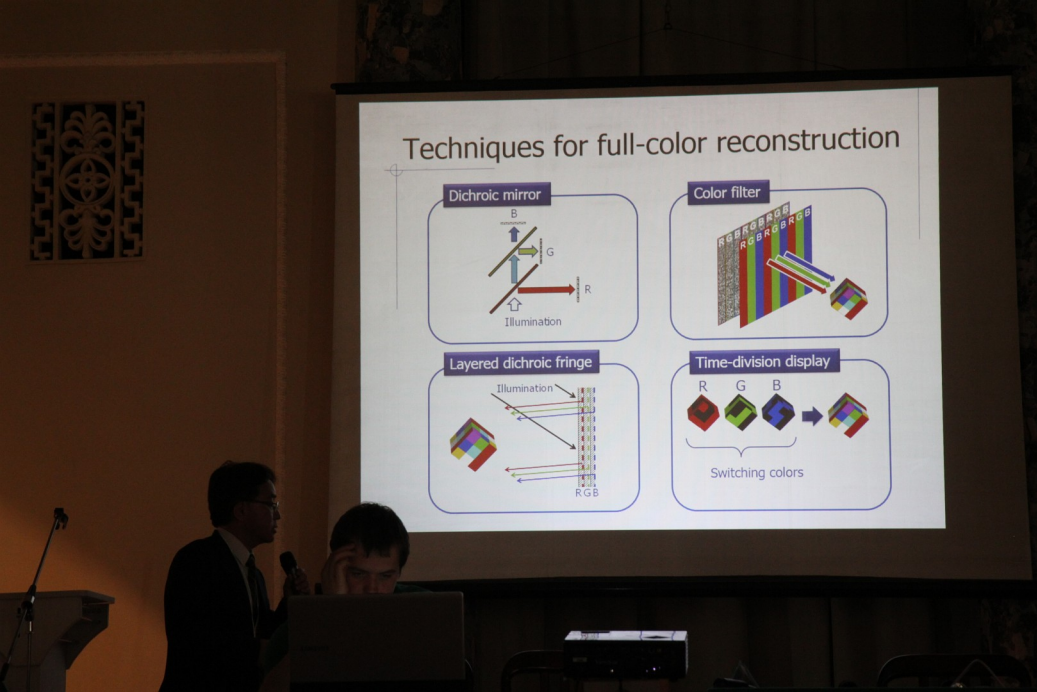
CGH reconstruction

- Switch back technique make it possible to compute the field of very complex models and simply convert the model to CGH.

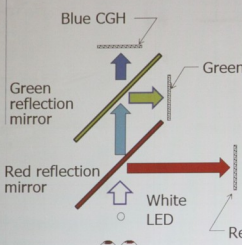
K. Matsushima, M. Nakamura, S. Nakahara, Opt. Express **22**, 24450 (2014)

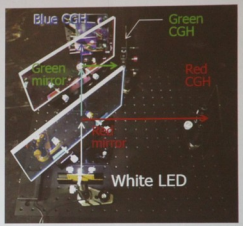
Optical reconstruction by white light

- No wavelength-selectivity unlike traditional volume-type holograms.
- Rainbow-like images
  - The size of the reconstructed image changes dependently on illuminated wavelength.


Techniques for full-color reconstruction
Dichroic mirror
B
G
R
Illumination
Color filter
Layered dichroic fringe
Illumination
R G B
Time-division display
R G B
Switching colors

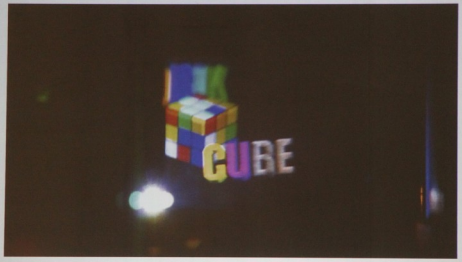
Full-color reconstruction using dichroic mirrors





- White light branches into RGB illumination by dichroic mirrors
- Reconstructed lights reversely travel along the illumination path and are combined by dichroic mirrors

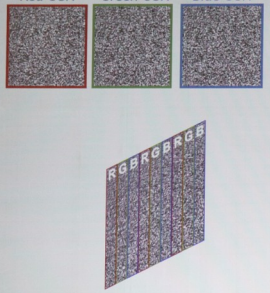
Full-color reconstruction using dichroic mirror



- Very good optical reconstruction
- No portability
- Optical system for superposition is complicated, heavy and expensive.

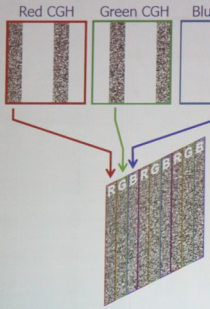
Full-color reconstruction using color filter

Red CGH Green CGH Blue CGH



- Single plate hologram
  - RGB fringes are split into many blocks.
  - RGB color filters cover up the corresponding fringe blocks.

Full-color reconstruction using color filter



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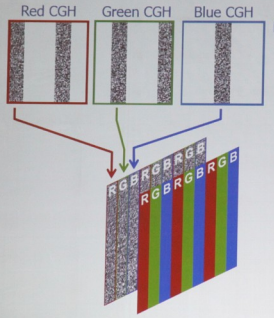
Full-color reconstruction using color filter



- Single plate hologram
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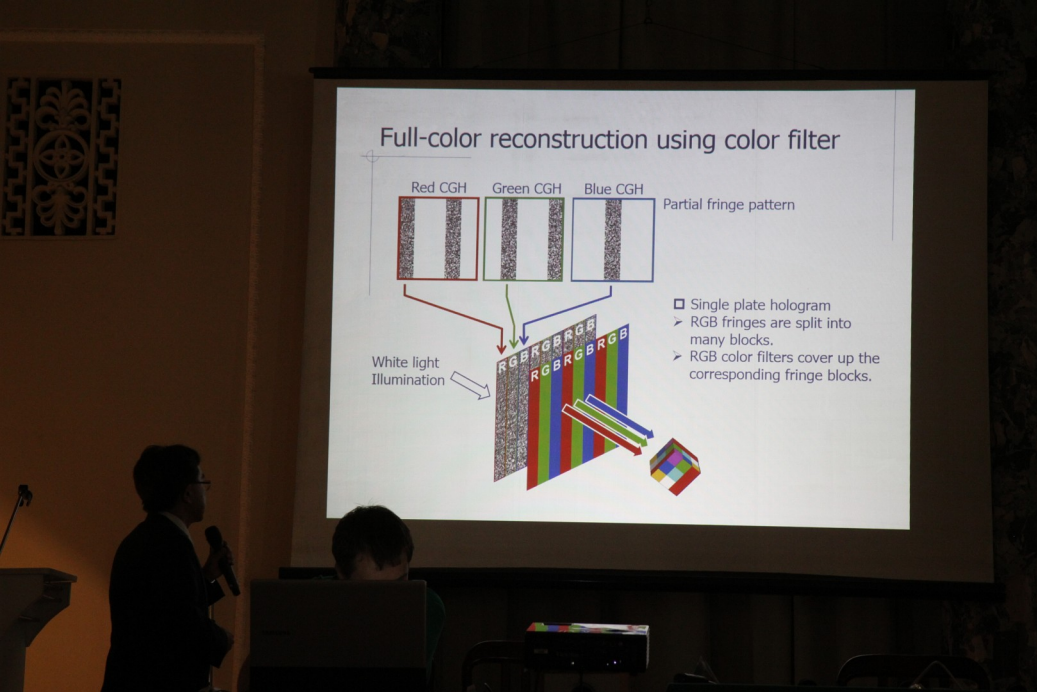
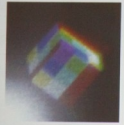

Full-color reconstruction using color filter
Red CGH
Green CGH
Blue CGH
Partial fringe pattern
White light
Illumination
R G B R G B R G B
R G B R G B R G B
Single plate hologram
RGB fringes are split into many blocks.
RGB color filters cover up the corresponding fringe blocks.

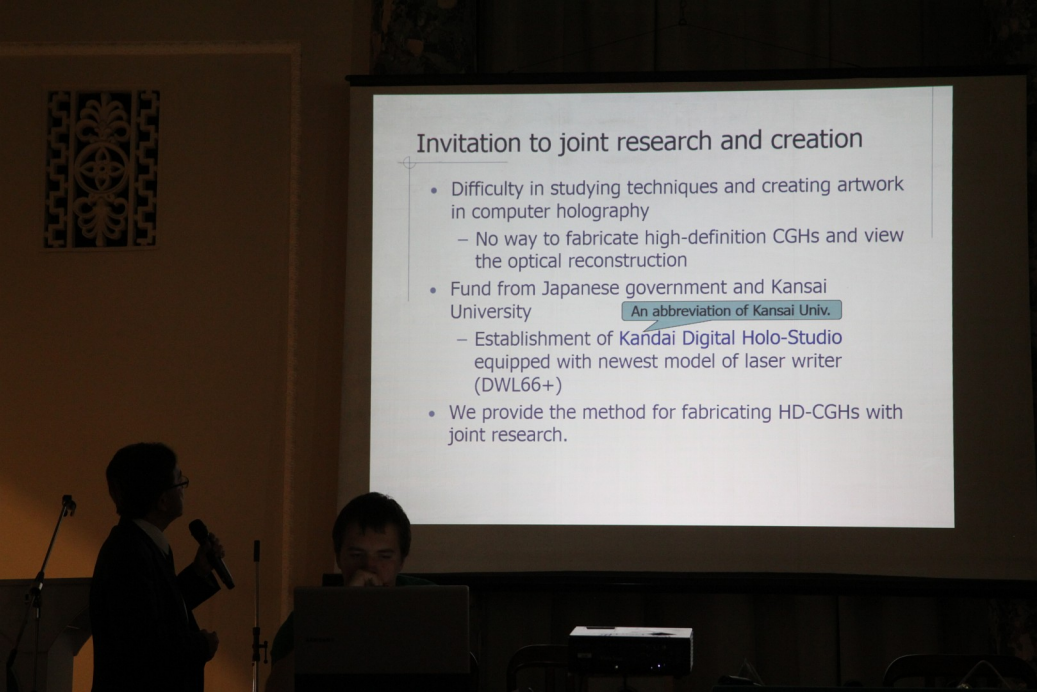
Example of full-color CGH using color filter



- Dark reconstructed image
- Difficulty in accurate positioning of filter with fringe block
- Double filtering in case of reflection reconstruction


HD-CGH printing service for research and creating artwork
KANDAI DIGITAL HOLO-STUDIO


Invitation to joint research and creation
• Difficulty in studying techniques and creating artwork in computer holography
– No way to fabricate high-definition CGHs and view the optical reconstruction
• Fund from Japanese government and Kansai University
An abbreviation of Kansai Univ.
– Establishment of Kandai Digital Holo-Studio equipped with newest model of laser writer (DWL66+)
• We provide the method for fabricating HD-CGHs with joint research.

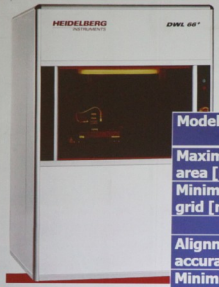
Facility provided for joint research

Laser writer

Model	Heidelberg Instruments DWL 66+	
Maximum drawing area [mm²]	200 × 200	
Minimum address grid [nm]	10	
	Mode I	Mode II
Alignment accuracy [nm]	100	120
Minimum structure size [μm]	0.6	0.8
Write speed [mm²/min]	4.0	16

Contact:
matsu@kansai-u.ac.jp

Facility provided for joint research



Printing is free of charge

You must provide fringe pattern generated by yourself

Laser writer

Model	Heidelberg Instruments DWL 66+	
Maximum drawing area [mm²]	200 × 200	
Minimum address grid [nm]	10	
	Mode I	Mode II
Alignment accuracy [nm]	100	120
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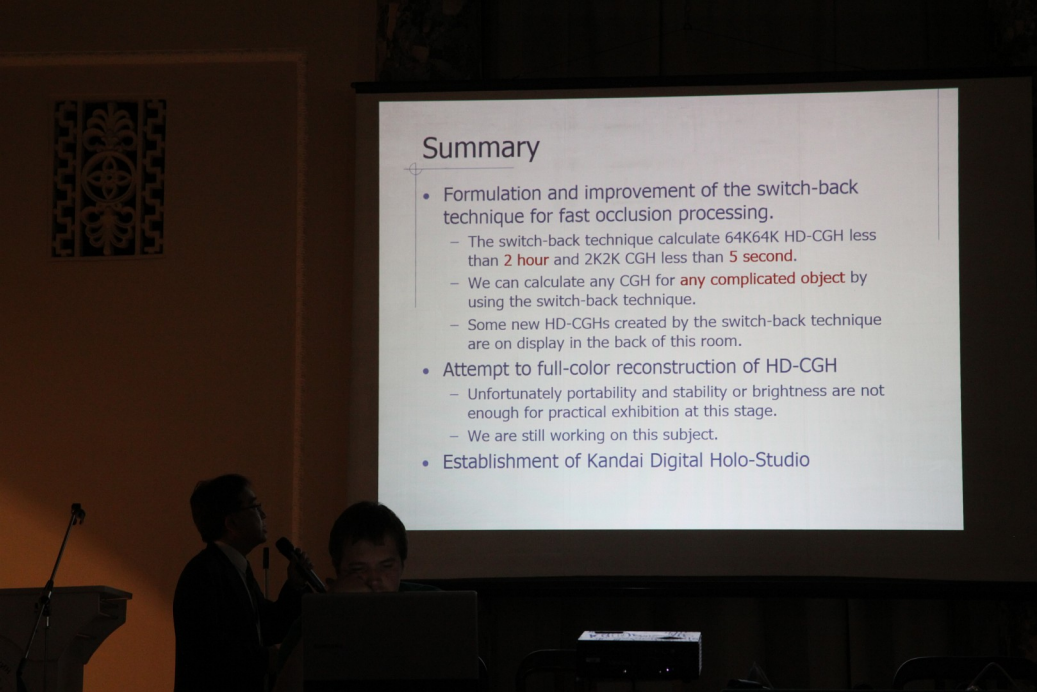
Summary
• Formulation and improvement of the switch-back technique for fast occlusion processing.
– The switch-back technique calculate 64K64K HD-CGH less than 2 hour and 2K2K CGH less than 5 second.
– We can calculate any CGH for any complicated object by using the switch-back technique.
– Some new HD-CGHs created by the switch-back technique are on display in the back of this room.
• Attempt to full-color reconstruction of HD-CGH
– Unfortunately portability and stability or brightness are not enough for practical exhibition at this stage.
– We are still working on this subject.
• Establishment of Kandai Digital Holo-Studio

Thank you!
(Sorry for poor English)

Ask me question later!