Optical encryption with random phase encoding in volume holographic storage

Wei-Chia Su
Optical Information Processing Laboratory
Graduate Program in Electro-Optical Engineering,
Tatung University, Taipei 104, TAIWAN

Ching-Cherng Sun
Dynamic Holography Laboratory
Institute of Optical Sciences, National Central University, Taiwan,
TAIWAN
Outline

• Introduction to volume holograms
• Encryption volume holographic storage
  -- 3D random phase multiplexing
  -- Encryption storage using PCRA
• Applications based on EVHS
  -- Spatial filters
  -- Interconnections
• Conclusions
Holography

- Object
- Reference
- Holographic Film
- Imaginary Image
- Real Image
- Conjugate Reference
- O
- R
- O*
- R*

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Volume Holograms

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Applications of Volume Hologram

• Data Base
  Storage Interconnection

• Filter
  Spatial/Temporal

• Phase Recorder
  Holography (3D display) Interferometer (Testing)

• Dynamic Response
  Optical Computing Associated Memory
  Neural Network

• Wave Mixing
  Image Amplification Phase Conjugation Mirror
Holographic Storage

- High Storage Capacity (~Tbit/cm$^3$)
- High Data Rate (~10Gbit/sec)
- Erasable
- Content Addressable Memory
- Optical Neural Network
Volume holographic storage

1024*1024 LiNbO$_3$ crystal
Photopolymer
3D storage vs. 2D storage

Volume holographic storage

- Volume \( \propto \frac{V}{\lambda^3} \)
- Parallel

Disk storage

- Planar \( \propto \frac{A}{\lambda^2} \)
- Series
Holographic Multiplexing

Angular multiplexing

Wavelength multiplexing

Phase multiplexing
Phase Multiplexing

Angular Multiplexing

Wavelength Multiplexing

Orthogonal Phase

Random Phase

Ground Glass

Multimode Fiber

Phase Spatial Light Modulators (PSLM)

Phase Spatial Light Modulators (PSLM)
Random Phase Generator:
A ground glass
A multi-mode fiber

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Orthogonal phase multiplexing -- SLM
vs. Random phase multiplexing -- ground glass

<table>
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<th>Advantage</th>
<th>Orthogonal Phase</th>
<th>Random Phase</th>
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<td></td>
<td>Better SNR</td>
<td>Easy and convenient</td>
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<td></td>
<td>--ground glass</td>
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<td>Security</td>
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<td>--phase is unpredictable</td>
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<td>Disadvantage</td>
<td>SLM</td>
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<td>Precise phase modulation</td>
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Encryption Storage

- Reference
- Ground glass
- Crystal
- Signal
- Diffraction
- Reading

- Writing
- Ground glass
- Crystal

- Reading
- Ground glass
- Crystal
- PCRA
3D Random Phase Multiplexing

Multi-layers Storage

Plane wave

GG

Crystal

Signal wave

S

S

S

R

R

R

3D Random Phase Multiplexing

3D Encryption Storage

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Security Holographic Storage

Random phase multiplexing
Multi-layers Storage
Encryption Storage

Random phase mask: key

ground glass is laterally shifted → Shifting sensitivity
Ground glass: random phase generator

\[ W(x_3, y_3) = \int_{\frac{y_2}{2}}^{\frac{y_2}{2}} \int_{\frac{x_2}{2}}^{\frac{x_2}{2}} A \cdot \exp\{j\phi(x_1, y_1)\} \cdot \exp\{jkr_1\} \cdot dx_1 \cdot dy_1 \]

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Owing to random phase distribution, the crosstalk between any two different points is suppressed. The effective diffraction occurs only when the grating is read by the original one.

\[
D = \int \int \int \int |A|^2 \cdot B \cdot \exp\left\{jk(x_2 - x_1)\right\} \cdot dx_1 \cdot dy_1 \cdot dx_2 \cdot dy_2 \cdot dx_3
\]

Paraxial approximation

Lateral shifting

\[
D = \int \int \int |A|^2 B \cdot \exp\left\{\frac{jk}{2z_0} \left[(x_3 - x_1 - \Delta x)^2 + (y_3 - y_1 - \Delta y)^2 - (x_3 - x_1)^2 - (y_3 - y_1)^2\right]\right\} \cdot dx_1 \cdot dy_1 \cdot dx_3
\]

Longitudinal shifting

\[
D = |A|^2 \cdot B \cdot \sum_{\Delta x} \sum_{\Delta y} \sum_{\Delta z} \exp\left\{j\left(\frac{z_0}{z} + \Delta z\right)^2 + (y_3 - y_1)^2 + (x_3 - x_1)^2\right\} \cdot \exp\left\{-j\left(\frac{z_0}{z} + \Delta z\right)^2 + (y_3 - y_1)^2 + (x_3 - x_1)^2\right\}
\]
3D shifting sensitivity

**Horizontal sensitivity**

\[ I \propto |D|^2 = (A_1 A_2 B \ell d / z_0^2)^2 \sin c^2 \left( \frac{\Delta x \cdot d}{\lambda z_0} \right) \sin c^2 \left( \frac{\Delta x \cdot \ell}{\lambda z_0} \right) \]

**Vertical sensitivity**

\[ I \propto |D|^2 = (|A|^2 B \ell d / z_0^2)^2 \sin c^2 \left( \frac{\Delta y \cdot d}{\lambda z_0} \right) \]

**Longitudinal sensitivity**

\[
D = |A|^2 \cdot B \cdot \sum_{y_i} \sum_{x_i} \sum_{d_0} \sum_{d} \left[ (z_0^2 + (y_i - y_j)^2 + (x_i - x_j)^2)^{1/2} \right]^2 \cdot \left[ (z_0 + \Delta z)^2 + (y_i - y_j)^2 + (x_i - x_j)^2 \right]^{1/2} \cdot \exp \left\{ jk [z_0 + \Delta z]^2 + (y_i - y_j)^2 + (x_i - x_j)^2 \right\} \cdot \exp \left\{ - jk [z_0^2 + (y_i - y_j)^2 + (x_i - x_j)^2]^{1/2} \right\}
\]
Experimental Setup

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Horizontal shifting tolerance

Normalized Diffraction Intensity

Horizontal Displacement of Ground Glass [µm]

Normalized Diffraction Intensity

Horizontal Displacement of Ground Glass [µm]

Normalized Diffraction Intensity

Horizontal Displacement of Ground Glass [µm]

Normalized Diffraction Intensity

Horizontal Displacement of Ground Glass [µm]
Roughness of GG
Lateral correlation of GG

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Vertical shifting tolerance

\begin{align*}
\text{Normalized Diffraction Intensity} \\
\text{Vertical Displacement of Ground Glass [\mu m]} \\
\end{align*}
Longitudinal shifting tolerance
Security storage using PCRA

Encryption

Decryption

Phase conjugation of reference beam
Optical security: decryption

Decryption image

Decrypted by another ground glass

Password
XYZ
85378

Shifting sensitivity
Impulse response

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Ground glass is laterally displaced at a distance $\Delta$

\[ R_2(x) = F^{-1}\{P_d(x_1)\} \]

\[ = \frac{\ell(d - \Delta)}{\lambda z_0} \cdot \text{sinc}\left(\frac{(d - \Delta)x}{\lambda f}\right) \cdot \text{sinc}\left(\frac{\ell \Delta}{\lambda z_0}\right) \cdot \exp\left(-\pi \frac{x\Delta}{\lambda f}\right) + N_2(x) \]

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Theoretical tolerance of GG

\[
R_2(x) = F^{-1}\{P_d(x_1)\}
= \frac{\ell(d - \Delta)}{\lambda z_0} \cdot \text{sinc}\left(\frac{(d - \Delta)x}{\lambda f}\right) \cdot \text{sinc}\left(\frac{\ell \Delta}{\lambda z_0}\right) \cdot \exp\left(-\pi \frac{xf}{\lambda f}\right) + N_2(x)
\]

when \(x=0\)

\[
I = \text{sinc}^2\left(\frac{\ell \Delta}{\lambda z_0}\right)
\]

\[
\text{sinc}^2\left(\frac{\ell \Delta}{\lambda z_0}\right) \quad \Rightarrow \quad \Delta = \frac{\lambda z_0}{\ell}
\]

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Ground glass with a pixel size \( w \)

\[
R(x) = F^{-1}\{p_d(x_1)\}
\]

\[
= F^{-1}\left\{ \sum_{m=-w}^{m+w} \frac{1}{2N+1} \cdot \frac{\ell \cdot w - |m|}{w} \cdot \frac{\ell(\Delta + m)}{\lambda z_0} \cdot \text{rect}\left( x_1 - \frac{\Delta + m/2}{d - (\Delta + m)} \right) \right\} + F^{-1}\{A(x) \cdot \exp[iB(x)]\}
\]

\[
= \sum_{m=-w}^{m+w} \frac{1}{2N+1} \cdot \frac{\ell \cdot [d - (\Delta + m)] \cdot w - |m|}{\lambda z_0} \cdot \frac{\ell(\Delta + m)}{w} \cdot \frac{\ell(\Delta + m)}{\lambda z_0} \cdot \frac{\ell(\Delta + m)}{\lambda z_0} \cdot \text{sinc}\left( \frac{d - (\Delta + m)x}{\lambda f} \right) \cdot \exp\left( -\pi \frac{x(\Delta + m)}{\lambda f} \right) + H(x)
\]
Experimental Setup

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Shifting tolerance of GG

\[ \Delta = \frac{\lambda z_o}{\ell} \]

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Lateral Shifting tolerance of various GG

\[ \ell = 10\, \text{mm}, \, L = 1.5\, \text{mm} \quad R = \left( \frac{L}{\ell} \right)^2 \]

Imperfection phase conjugation wave

\[ R_i(x) = \sum_{m=-\infty}^{\infty} \frac{1}{2N+1} \cdot \frac{\ell \cdot [d - (\Delta + m)]}{\lambda z_0} \cdot \frac{w - m}{w} \cdot \text{sinc} \left( \frac{\ell(\Delta + m)}{\lambda z_0} \right) \cdot \text{sinc} \left( \frac{[d - (\Delta + m)]x}{\lambda f} \right) \cdot \exp \left( -\frac{\pi x(\Delta + m)}{\lambda f} \right) + H(x) \]
All-optical fiber sensing system
Fiber Sensing vs. Speckle

A, B, C ...

A → S1
B → S2
C → S3

S1
S2
S3
Interconnection Between Speckles and Displays Through Volume Holograms

Reading

Input

Output

S1 → 0100 μm → S2 → 0050 μm → S3 → 0000 μm
Diffraction results of optical sensing system
Translation System: Pattern interconnection

Writing

Reading

Perform translation function
Experimental setup

Writing process
Experimental and simulation diffraction results

Reading images

Experimental diffraction images

Simulation diffraction images

Input English word pattern
Confocal microscopy system

- LiNbO$_3$
- Translation Stage
- Mirror
- Beam Splitter
- Translation Stage
Confocal microscopy

Ar+ Laser (514.5nm)  

Normalized Diffraction Intensity

Longitudinal Shifting [μm]

NA=0.52

Normalized Diffraction Intensity

Longitudinal Shifting [μm]

NA=0.817
Angular sensing system

Indicate the angular deviation of the crystal
Diffraction results of angular sensing system

-0.025°
-0.020°
-0.015°
-0.010°
-0.005°
0°
0.005°
0.010°
0.015°
0.020°
0.025°

φ: Angular deviation of the crystal
Resolution of the angular sensing system

The crystal is rotated laterally at a small angle in the horizontal direction, it is equivalent to the lateral displacement of the point source.

Shifting selectivity \( \delta x = \frac{\lambda z_o}{\ell} \)

Angular selectivity \( \delta \theta = \frac{\delta x}{z_o} \)

Conclusions

Optical sensing
Optical interconnection
Optical security (encryption)
Optical storage

3D random phase multiplexing encryption multi-layer