Pulse Storage Using Wavelength Multiplexed Holograms in Photorefractive Crystal.

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OUTLINE

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Motivation

• **All-optical delay is important for many applications.**
  – Optical delay line/buffer
  – Synchronization
  – Jitter correction
  – Interferometry, spectroscopy

• **Many recent experimental demonstrations.**
  – Engineered resonances (photonic crystal WG, FP, FBG,…)
  – Stimulated gain/absorption processes (SBS, SRS)
  – Nonlinear methods (wavelength conversion/dispersion)
  – Stopped light (EIT in atomic vapor)

• **All of these systems seek**
  – Maximum tunable delay
  – Minimum pulse distortion (High data fidelity)
Background: PR effect

- PR holography is powerful for the data storage with high data fidelity.
- Photo-refractive (PR) effect

The gradient of the electric field is proportional to space charge. → \( \pi/2 \) phase shift

- \( \Delta n = \frac{1}{2} n^3 r_{\text{eff}} E_{\text{SC}} \)

where \( r_{\text{eff}} \) E-O coefficient
Holographic Recording & Readout

- Bragg selectivity enables to multiplex holograms. (Bragg condition: $\lambda = 2n\Lambda \sin \theta$)

- Information recording

- 3 objects, 3 different wavelengths ($\lambda_1, \lambda_2, \lambda_3$)
- $n$ objects, $n$ different wavelengths ($\lambda_1, \ldots, \lambda_n$)

- Grating efficiency,

$$\eta = \left| \frac{E_d}{E_s} \right|^2 \approx \text{sinc}^2 \left( \frac{2L\Delta\lambda \sin^2 (0.5(\theta_s + \theta_r))}{\lambda^2 \cos \theta_s} \right)$$

- Information readout

- Efficiency vs. $\Delta\lambda$
  
  L=6mm, $\lambda=500$nm, and $\theta_s=\theta_r=45^\circ$,
PR delay Technique

- PR system design,
  - Record

- Fractional delay, \( T_d = \frac{\text{Stored Time}}{\text{Pulse Period}} = \frac{\Delta T_d}{T_p} \)

- Wavelength conversion: SFG or SHG

- Amplified power decide system limit.

- PR materials have the maximum sensitivity at \( \lambda \)'s.
  \( \rightarrow \) SBN and BaTiO\(_3\) : \( \lambda \approx 500\text{nm} \),
  \( \rightarrow \) BaTiO\(_3\) and LiNbO\(_3\) : \( \lambda \approx 600\text{nm} \)

- Single bit \( \rightarrow \) Single hologram,
  - Multiple bits \( \rightarrow \) Multiplexed holograms

Input Data in fiber, \( \lambda = 1550\text{nm} \)

Synchronization for \( \lambda \) Multiplexing

\( \lambda \) or \( \theta \):

Signal
Reference

\( T_p \)

Reference for readout
PR delay Technique

- PR system design,
  - Retrieve
  - Fractional delay, \( T_d = \frac{\text{Stored Time}}{\text{Pulse Period}} = \frac{\Delta T_d}{T_p} \)
  - Wavelength conversion: SFG or SHG
  - Amplified power decide system limit.
  - PR materials have the maximum sensitivity at \( \lambda \)’s.
    → SBN and BaTiO\(_3\) : \( \lambda \approx 500\text{nm} \),
    → BaTiO\(_3\) and LiNbO\(_3\) : \( \lambda \approx 600\text{nm} \)
  - Single bit → Single hologram,
    Multiple bits → Multiplexed holograms

Reference for readout: all ones [1 1 1... 1 1].
Single Hologram Diffraction efficiency (DE)

- DE, power, and exposure time are important issues for the system design.
- The peak diffraction efficiency for single hologram
  \[ \eta = \left( \frac{\pi \eta_q n^3 r_{\text{eff}}^e \alpha L PT_p}{2\varepsilon_s h c K A} \right)^2 \]

- DE for different pulse widths, using 13mm SBN75 crystal.
- Available power and exposure time decide system performance.

\[ \eta \propto (PT_p)^2 \]

- For high speed, exposure time is small, requires high power.
- YDF(ytterbium-doped fiber) MOPA source
  \[ \Rightarrow P = 15kW \quad [1] \]
  \[ P=15kW \Rightarrow \eta = 10^{-4} \text{ at BR}=1\text{Gbps}. \]
- Commercially available detector sensitivity:
  \[ -38\text{dBm} \Rightarrow \eta = 1.58 \times 10^{-7} \]

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DE for multiple holograms at BR=1Gbps

- The DE for the $m$th hologram,
  \[ \eta_m = \frac{\eta}{M^2} \left( \frac{t_m}{\tau_w} \right)^2 \exp\left[ -\sum_{i=m+1}^{M} \frac{t_i}{\tau_e} \right], \]
  where $\tau_w$, $\tau_e$, and $t_m$ are writing-, erasure-, exposure-time.

- $\eta_m \propto 1/M^2$

- Uniform efficiency for all holograms: 
  
  Exposure schedule (ES) $\rightarrow$ To make all of the diffracted output bits with equal intensity by appropriately allocating different power levels to each bit.

For 13mm SBN75, BR=1Gbps

<table>
<thead>
<tr>
<th>Power</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1kW</td>
<td>17 bits</td>
</tr>
<tr>
<td>2kW</td>
<td>35 bits</td>
</tr>
<tr>
<td>3kW</td>
<td>50 bits</td>
</tr>
</tbody>
</table>
Angle Multiplexing

- Now, Bragg selectivity enables to multiplex holograms with $\theta$.

### Experimental setup

- **Record**
  - Laser
  - Modulator
  - ND filter
  - BS
  - KNSBN
  - Motorized rotating mirror
  - Lens
  - Iris
  - Detector

- **Retrieve**
  - Laser
  - Modulator
  - ND filter
  - BS
  - Shutter
  - KNSBN
  - Detector

### Experimental conditions:

- **6 mm KNSBN, $T_p=5$ sec**
- **Angular selectivity** $\Delta \theta = \lambda / a$
  \[ \Delta \theta = 0.02^\circ (= 7 \times 10^{-4} \text{ rad}) \text{ for } a \sim 1 \text{ mm and } \lambda = 0.5 \text{ um, where } a \text{ is beam diameter.} \]

- **Synchronization**
- **Bragg matching**
Experimental results for angle multiplexing

- Record and retrieve 7 bits with different write and read power.
- NRZ pulse ($T_p = 5$ sec), $\Delta \theta = 0.02^\circ$.
- Storage time $\approx 120$ sec (2 min).

Simulation and experimental results agree well.

**Fraction delay $\approx 24$**

$$SNR = \frac{u_1 - u_0}{\sqrt{\sigma_1^2 + \sigma_0^2}}$$

- High $SNR \geq 10 \rightarrow$ Good data fidelity.
- No exposure schedule is used, so that grating decay is observed.
Conclusions

- All-optical delay systems require large delay with high fidelity.

- Experimental results for angle multiplexing show large tunable delay ($FD \approx 24$) with high SNR ($\geq 10$) for $T_p = 5$ sec.

- Design study for wavelength multiplexing shows feasibility of large delay. Under the given $P = 2kW$, 35 bits can be stored and retrieved at $BR = 1Gbps$.

- Sufficient large delay with good data fidelity is possible by considering long dark storage time.

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<tr>
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</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>1msec</td>
<td>1.42bits</td>
<td>$10^6$</td>
</tr>
<tr>
<td>BaTiO3</td>
<td>10sec</td>
<td>17bits</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>SBN</td>
<td>1hour-30days</td>
<td>35bits</td>
<td>$3.6 \times 10^{12}$-$2.5 \times 10^{15}$</td>
</tr>
<tr>
<td>LiNbO3</td>
<td>Up to 1year</td>
<td>350bits</td>
<td>$3.2 \times 10^{16}$</td>
</tr>
</tbody>
</table>

Summary for different PR crystals

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