Towards eternal archive via 5D optical data storage in glass

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➢ It is estimated that at least \textit{million terabytes} of data are generated every day.

➢ The size of collections in Library of Congress is \textit{20 thousand terabytes}.

➢ Brain’s memory capacity is in the \textit{thousand terabytes} range, as much as entire Web.

\text{Terabyte} = 10^{12} \text{ Bytes}
Long-term data preservation

- Nature’s choice: DNA (1M years @ -18 °C)
- Current archiving technology: Magnetic tape (20 years)
- Optical based technologies: CD or DVD (10 years)
  - M-Disc (1000 years)
  - Quartz glass (100M years)
Optical data storage benefits

- **Longevity**: "Optical" recording has been used for over 10,000 years in human data recording history.
- **Compatibility**: Since BD can be read on general purpose PCs with consumer devices, there is less possibility that media and data will be inaccessible due to obsolete devices.
- **Contactless**: Since there is no contact with the media surface, there is less possibility of abrasion, scratch or other media wear.
- **Survivability**: Only data stored on optical disc survived hurricane Katrina.

Courtesy: *Optical Media Roadmap*

*"The revival of Optical Storage"*

Ken Wood
Hitachi Data Systems
Femtosecond laser direct writing: The principle

- Tight focusing of laser beam (e.g. $\lambda = 800$ nm, $\Delta \tau = 100$ fs) into transparent material
- High intensity leading to multi-photon absorption
- Structural changes in matter confined to focal volume due to short pulse duration – 3D

Intensity $\sim 5 \times 10^{13}$ W/cm$^2$
Electron temperature $\sim 10^5$ K /10 eV
Pressure $\sim 10^6$ bar
3D optical storage by femtosecond laser writing

Picosecond (10 x 10^{-12} s) laser induces voids *with external stress*

Femtosecond (100 x 10^{-15} s) laser induced *small* voids in quartz glass

Femtosecond lasers perform vision-correction surgery
Ultrafast-laser nanostructured (ULN) quartz glass: The finest bulk ripple ever produced by light

Ripples on Earth and in space
Self-organized form birefringence

Femtosecond laser nanostructured quartz glass: $n_e - n_o = -5 \times 10^{-3}$

Quartz crystal: $n_e - n_o = 9 \times 10^{-3}$
Light logo imprinted by femtosecond laser self-assembled nanostuctures in glass
Nanogratings produce birefringence characterized by two parameters:

(4thD) Retardance $R = |n_x - n_y| \times d$

(5thD) Slow axis angle $\theta$
How it works?

- Position: 3 spatial dimensions
- Retardance = $f(\text{Intensity, Number of pulses})$
- Slow axis = $f(\text{Polarization})$

1 Byte (8 bits) per spot:
- 32 states (5 bits) of slow axis orientation
- 8 states (3 bits) of retardance
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>CD</th>
<th>DVD</th>
<th>Blue-ray</th>
<th>5D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>0.7 GB</td>
<td>4.7 GB</td>
<td>23.5 GB</td>
<td>360TB per disc</td>
</tr>
<tr>
<td>Longevity</td>
<td>5 years</td>
<td>7 years</td>
<td>7 years</td>
<td>10^{20} years</td>
</tr>
<tr>
<td>Speed</td>
<td>1.2 Mbit/s (1x)</td>
<td>10.5 Mbit/s (1x)</td>
<td>36 Mbit/s (1x)</td>
<td>200 Mbit/s</td>
</tr>
</tbody>
</table>

- **Current writing speed:** 12 Kbits/s
- **Current capacity:** 100 GB/disc
- **5 bits per dot**

Advantages of 5D in quartz glass: High capacity, Long life time
Using the Arrhenius law, the lifetime can be extrapolated to the room temperature.

\[ R(t) = R_0 \times e^{-t/\tau} \]

\( T = 900^\circ \) -> \( \tau = 121 \text{ h} \)

\( T = 1000^\circ \) -> \( \tau = 32 \text{ h} \)

\( T = 1100^\circ \) -> \( \tau = 9 \text{ h} \)

\( T = 30^\circ \) -> \( \tau = 300 \times 10^{18} \text{ years} \)
Superman's memory crystals may become reality in computers

Computers may soon be saving their data onto hard drives made of glass following research by British scientists who have developed a way of storing information similar to the "memory crystals" seen in the Superman films.
Data writing

Retardance

Slow axis orientation
Readout

20 µm

130 µm
The idea of the optical memory based on femtosecond laser writing in the bulk of transparent material was first proposed in 1996 [1]. More recently ultrafast laser writing of self-assembled nanogratings in class $\text{sa}_3$ proposed for the polarization multiplex optical memory, where the information encoding would be realized by means of two birefringence parameters, i.e. the slow axis orientation (4th dimension) and length of retardance (5th dimension), addition to three spatial coordinates [2, 3]. The slow axis orientation and the retardance can be controlled by polarization and intensity of the incident beam respectively [4]. The unprecedented parameters including 360 TB/disc data capacity, thermal stability to 1000°C and practically unlimited lifetime [5]. However the implementation of digital storage, which is a crucial step towards the real world applications, has not been demonstrated by ultrafast laser writing.

Here we successfully recorded and retrieved a digital copy of the text file in 5D using polarization controlled ultrafast laser nanostructuring in silica glass.

Data retrieved

42 bits errors out of 11664 bits (1458 bytes):
Error rate 0.36%
TO COMMEMORATE
THE FIRST EDITION OF NEWTON’S
OPTICKS

5D OPTICAL MEMORY
Coded text
8 layers
Ø 1.4mm
in 0.254mm fused silica
glass
Δx = 15μm
200GB/cm³

3D

4thD Slow axis angle

5thD Retardance
Magna Carta coded in 5D

Courtesy: Ausra Cerkauskaite and Rokas Drevinskas
The eternal copy of UDHR presented to UNESCO at the Year of Light closing ceremony in Mexico
Asteroid of 10 km in diameter collided with Earth 65 million years ago causing mass extinction.

Ultrafast-laser nanostructured (ULN) fused quartz

Coincidently, the lamella structures of ULN fused quartz and shocked quartz are similar.
Southampton time capsule in quartz glass

This information was recorded for future generations by Jingyu Zhang, Mindaugas Genovicius, Martynas Beresna and Peter G. Kazansky (Петр Георгиевич Казанский) located in building 46, University of Southampton, United Kingdom, planet Earth.
Conclusions

- Optical data storage with practically unlimited lifetime in ultrafast laser nanostructured quartz glass is demonstrated.

- For the first time, storage technology might allow human knowledge to outlive us.
It has been hailed as a particular significant invention as no other storage medium can so safely ensure that data will be accessible by future generations.