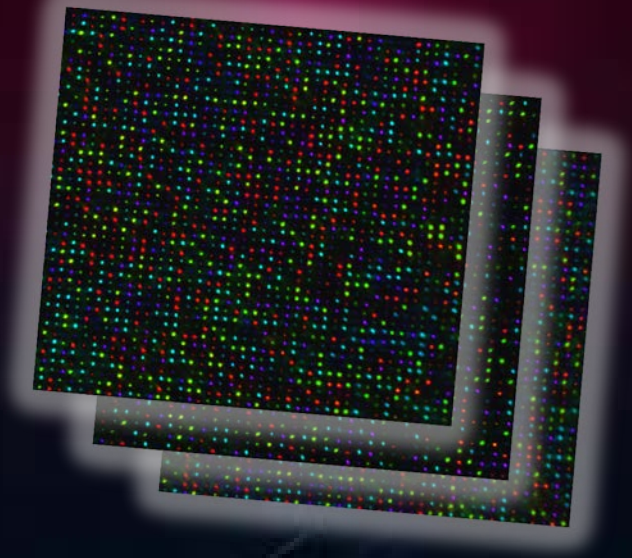
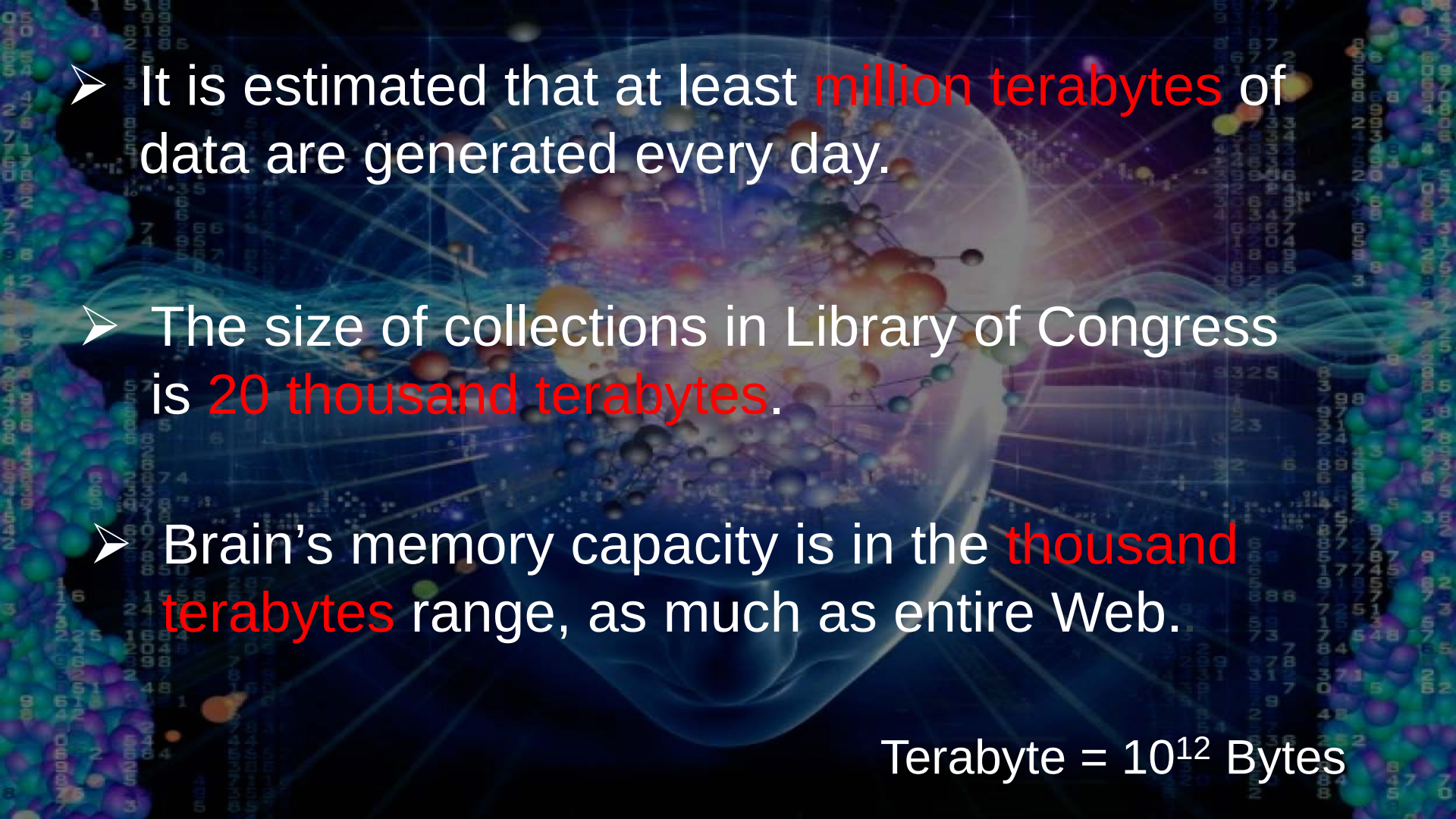
Towards eternal archive via 5D optical data storage in glass



Peter G. Kazansky

Optoelectronics Research Centre, University of Southampton

erendipity hotonics

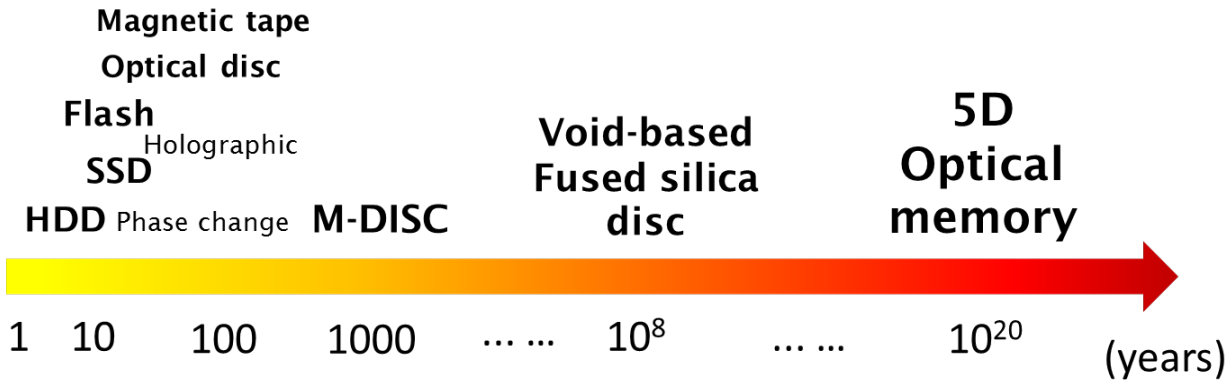


- It is estimated that at least million terabytes of data are generated every day.
- The size of collections in Library of Congress is 20 thousand terabytes.
- Brain’s memory capacity is in the thousand terabytes range, as much as entire Web.

Terabyte = 10^{12} Bytes

Long-term data preservation

- Nature's choice: DNA (1M years @ -18 ^{o}C)
- Current archiving technology: Magnetic tape (20 years)
- Optical based technologies: CD or DVD (10 years)
  M-Disc (1000 years)
  Quartz glass (100M years)

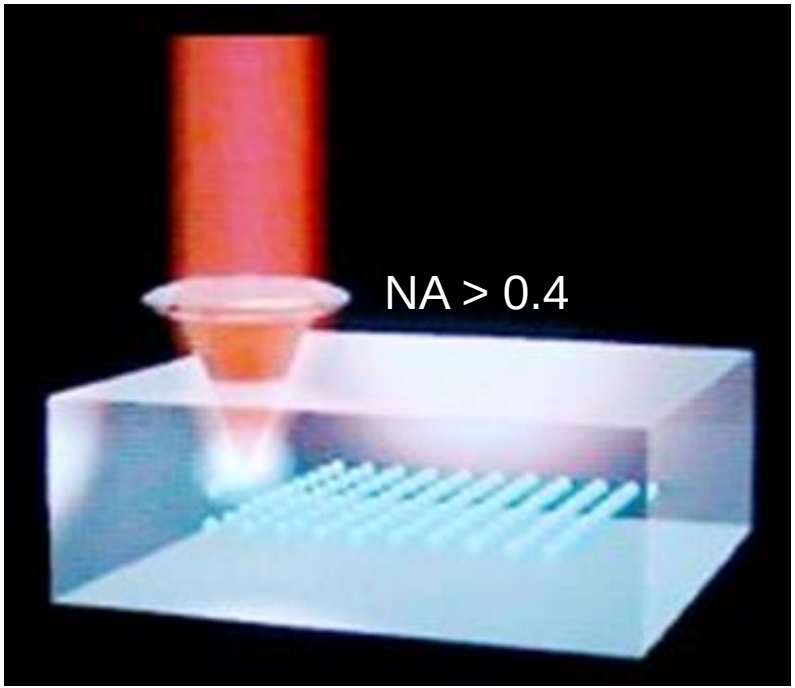


Optical data storage benefits

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. λ =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

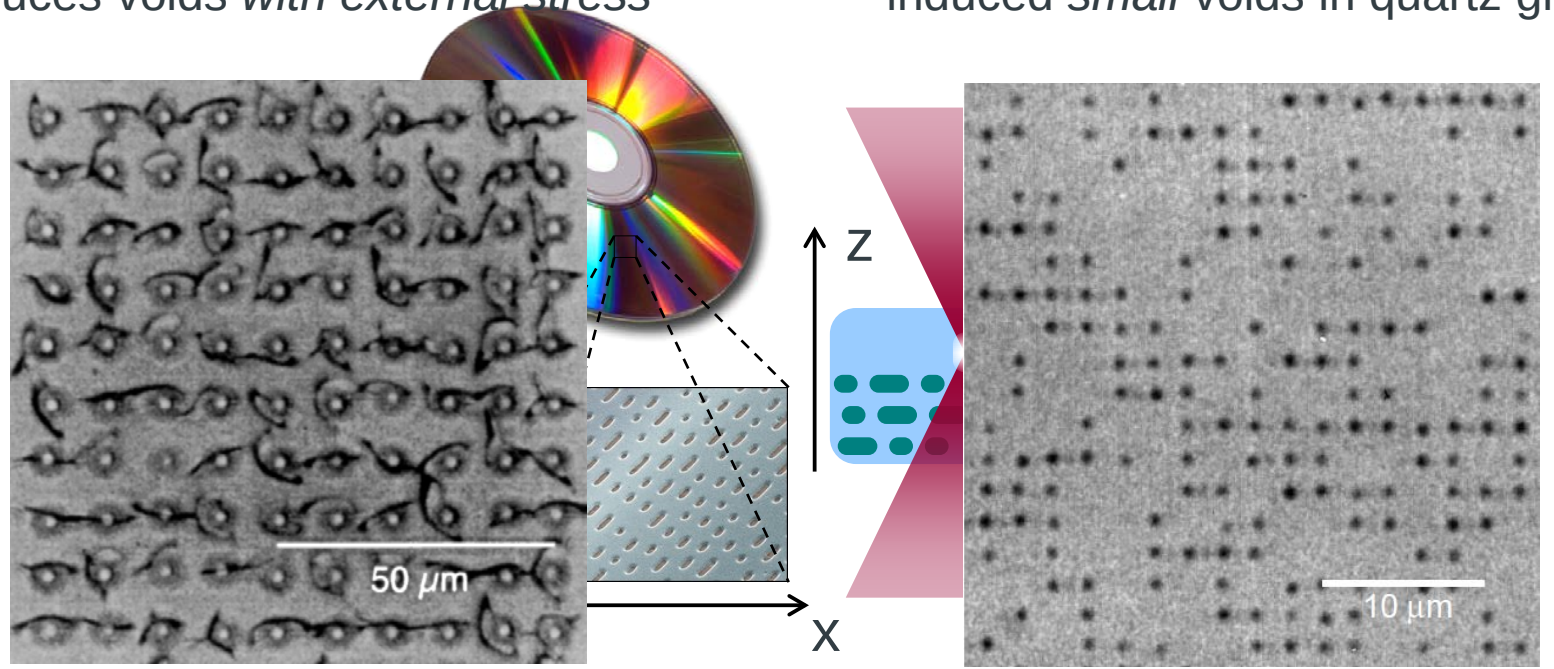


Intensity ~ 5×10^{13} W/cm^2
Electron temperature ~ 10^5 K /10 eV
Pressure ~ 10^6 bar

3D optical storage by femtosecond laser writing

Picosecond (10 x10^{-12} s) laser induces voids *with external stress*

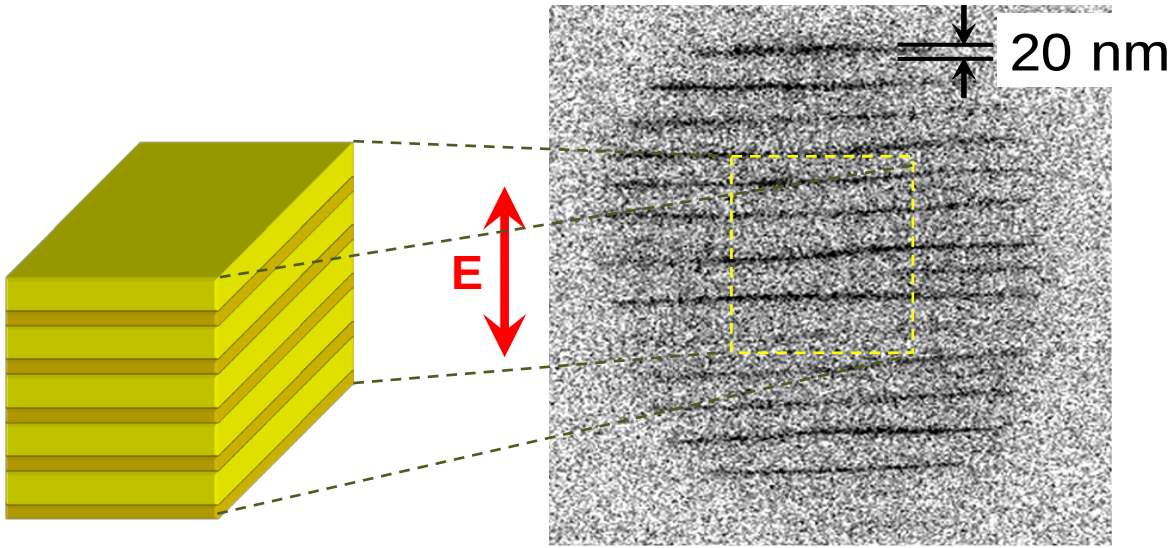
Femtosecond (100 x 10^{-15} s) laser induced *small* voids in quartz glass



Glezer et al.,*Optics Letters* (1996)

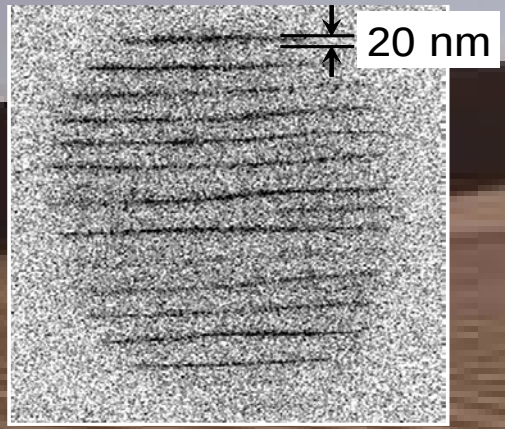
Femtosecond lasers perform vision-correction surgery

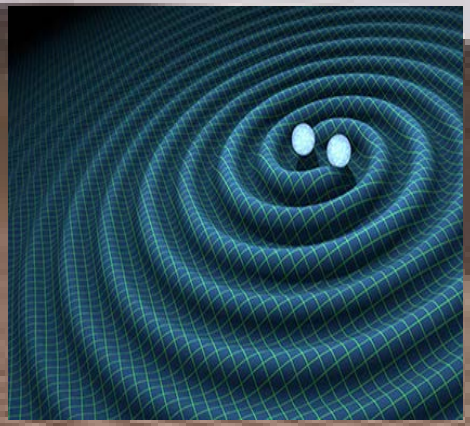
Ultrafast-laser nanostructured (ULN) quartz glass: The finest bulk ripple ever produced by light



P.G. Kazansky et al., *Phys. Rev. Lett.,* **82**, 2199 (1999)
Y. Shimotsuma et al., *Phys. Rev. Lett.* **91,** 247405 (2003)

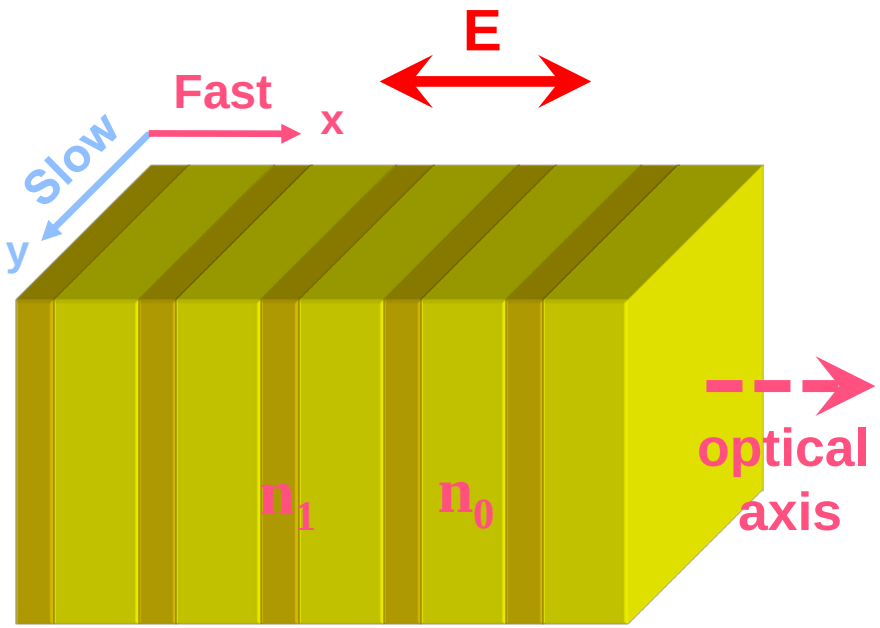
Ripples on Earth and in space





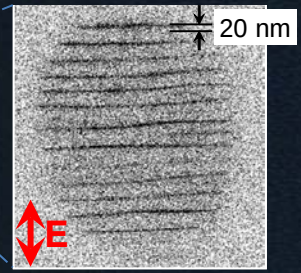
Self-organized form birefringence

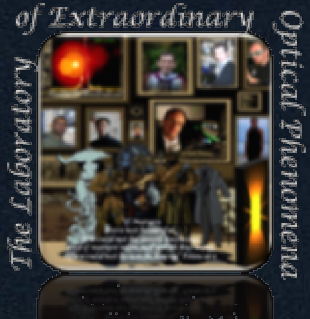
Femtosecond laser nanostructured quartz glass: $n_e - n_o = -5 \times 10^{-3}$



Quartz crystal: $n_e - n_o = 9 \times 10^{-3}$

Light logo imprinted by femtosecond laser self-assembled nanostuctures in glass



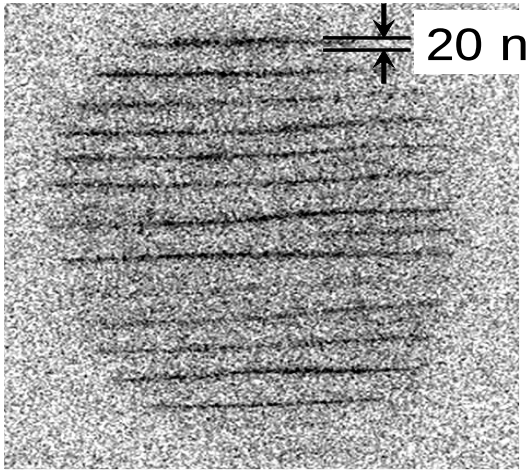


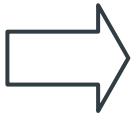
4th and 5th dimensions: Retardance and slow axis angle

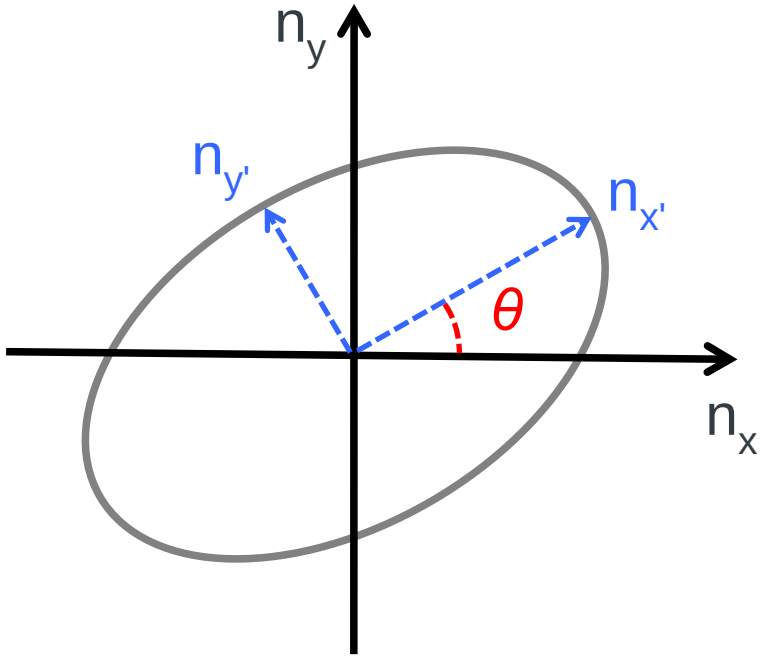
Nanogratings produce birefringence characterized by two parameters:

(4thD) Retardance $R = |n_{x'}-n_{y'}|\times d$

(5thD) Slow axis angle θ







How it works?

- ✓ Position: 3 spatial dimensions
- ✓ Retardance = f(*Intensity, Number of pulses*)
- ✓ Slow axis = f(*Polarization*)

1 Byte (8 bits) per spot:

32 states (5 bits) of slow axis orientation
8 states (3 bits) of retardance

Comparison

	CD	DVD	Blue-ray	5D
Capacity	0.7 GB	4.7 GB	23.5GB	360TB per disc
Longevity	5 years	7 years	7 years	10^20 years
Speed	1.2 Mbit/s (1x)	10.5 Mbit/s (1x)	36 Mbit/s (1x)	200 Mbit/s

Current writing speed: 12 Kbits/s

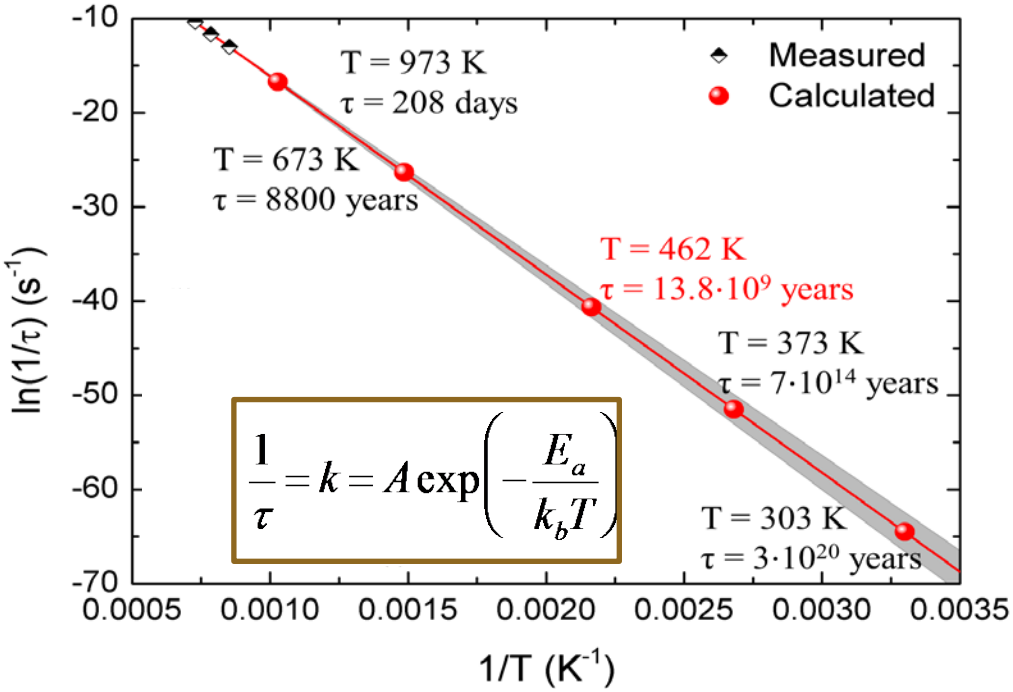
Current capacity: 100 GB/disc

5 bits per dot

Advantages of 5D in quartz glass: High capacity

Long life time

Thermal stability



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

T = 900° -> τ = 121 h

T = 1000° -> τ = 32 h

T = 1100° -> τ = 9 h

Using the Arrhenius law,
the lifetime can be extrapolated
to the room temperature

T = 30° -> $\tau = 300 \times 10^{18}$ years

Two images in one day of

The Telegraph

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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.

The glass memory has been compared to the 'memory crystals' used in the Superman films

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Technology News

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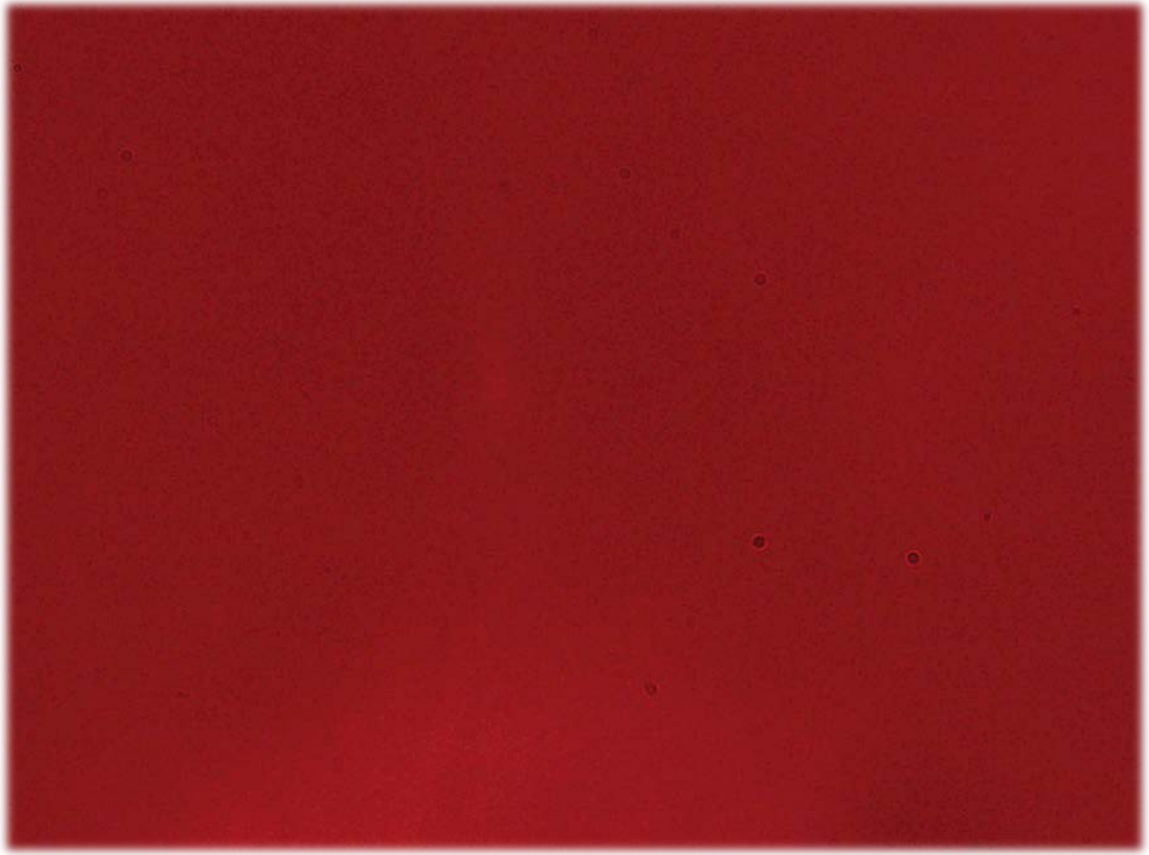
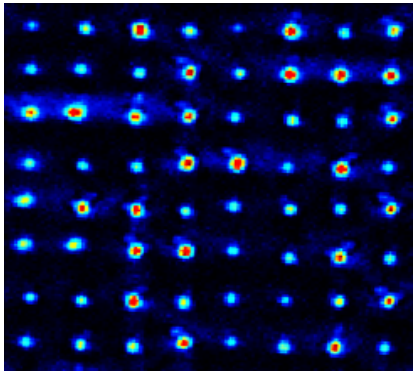
of slow axis

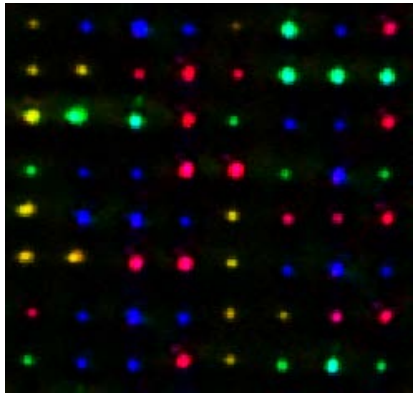
Data writing



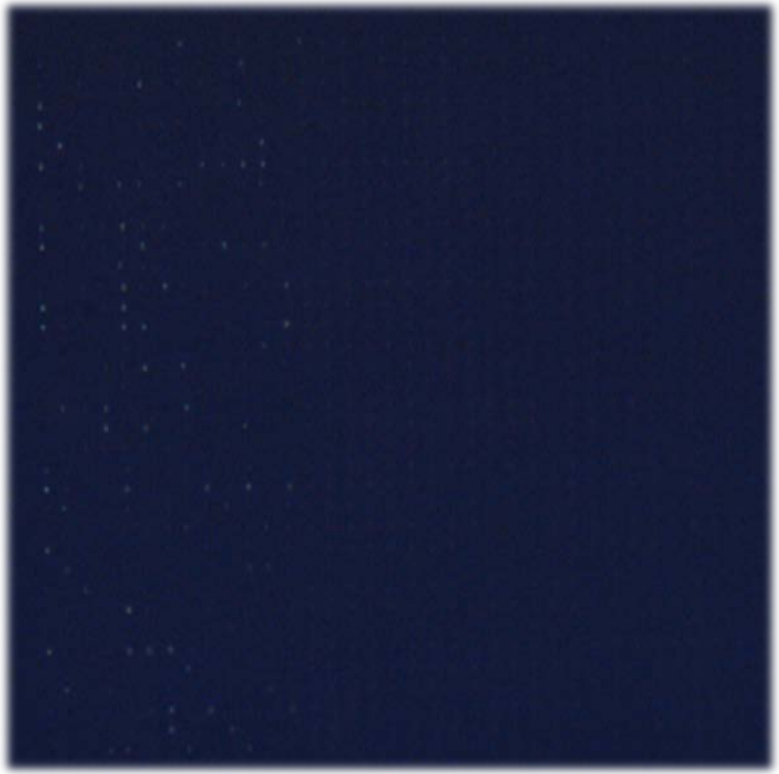
Retardance

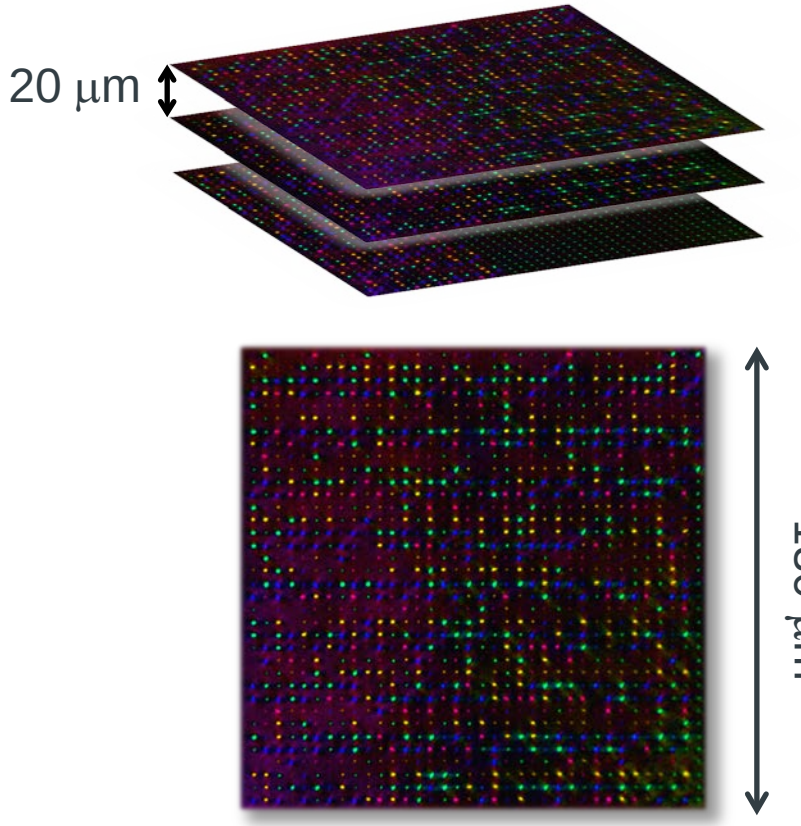


Slow axis orientation



Readout





Data retrieved

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 **s**a**3** proposed for the polarization m**5**ltiplex**E**d optical memory, where the information encoding would be realized by means of two birefringenc**m** parameters, i.e. the sl**g**w axis orientation (4th dimension) and s**42**ength of retardance (5th dimension), **)f** addition to three spatial coordinates [2,³]. The slow axi**{** orientation **á**nd the retardance can be controlled by polarization and intensity of the`inciden**ô** beam respectively [4]. The unprecedented parameters including 360 TB/disc data capacity, thermal stabilit **5**p to 1000˚ C and practically unlimited lifetime [5]. However the implementation of digi**4**al d**!4**a storage, whi**b**h is a cruc**a**al step t**k**wards the real world applications, has not **"**een demonst**2**ated by ultraf**!**st laser **s**riting. Here we success**n**ully recorded and`retriev**g**d a`di**o**i**u**al copy□f the text **æ**ile in 5D using polarization controlled se**m**f-assembled`ultrafa**ó**t laser nano**{p**ructuring in silica glass.

42 bits errors
out of 11664 bits
(1458 bytes):
Error rate 0.36%

United Nations Educational, Scientific and Cultural Organization

INTERNATIONAL YEAR OF LIGHT 2015

UNIVERSITY OF Southampton

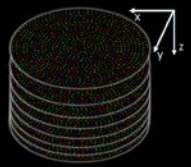
TO COMMEMORATE THE FIRST EDITION OF NEWTON'S *OPTICKS*

5D OPTICAL MEMORY

Coded text

8 layers
Ø 1.4mm
in Ø25.4mm
fused silica
glass
$\Delta z = 15\mu m$
$200GB/cm^3$

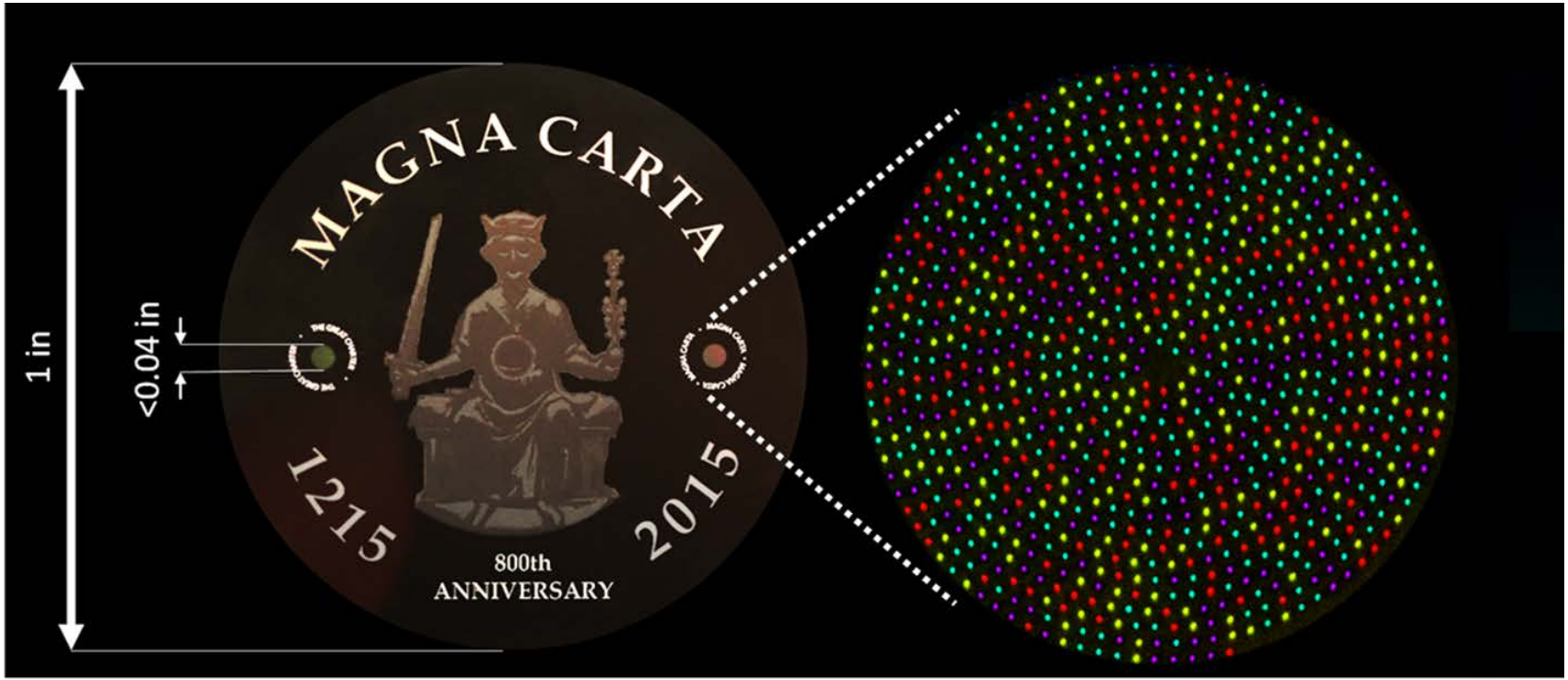
3D

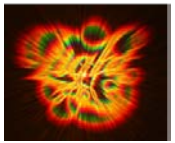


4thD Slow axis angle

5thD Retardance

Magna Carta coded in 5D



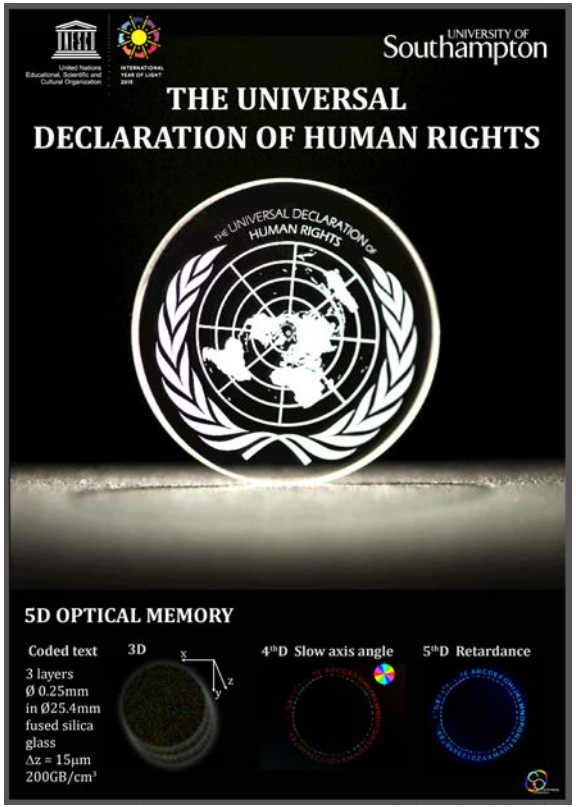


Courtesy: Ausra Cerkauskaite and Rokas Drevinskas

serendipity photonics

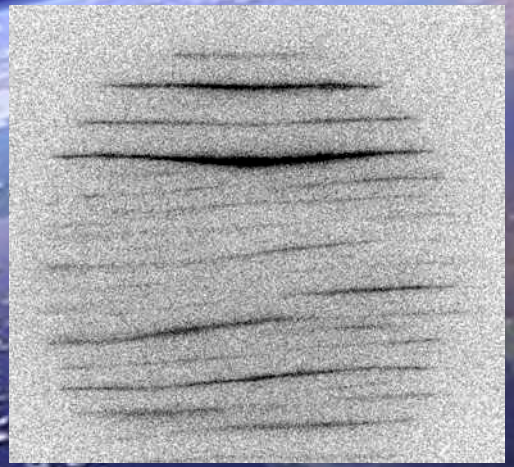

Magna Carta 1215
Happened and Why?
Magna Carta:
Spirit of Justice–
Power of Words
MAGNA CARTA
2015

The eternal copy of UDHR presented to UNESCO at the Year of Light closing ceremony in Mexico



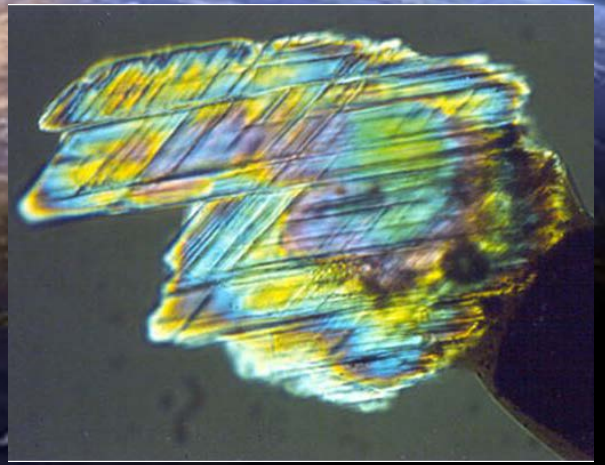
Asteroid of 10 km in diameter collided with Earth 65 million years ago causing mass extinction

Ultrafast-laser nanostructured (ULN) fused quartz



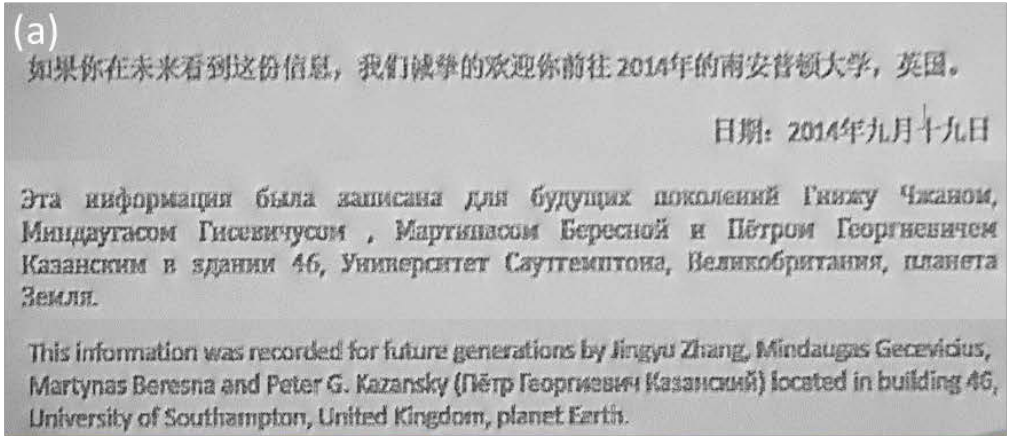
Chicxulub

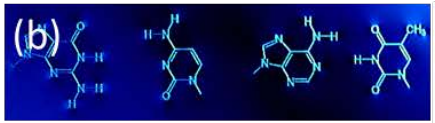
Shocked quartz at impact site

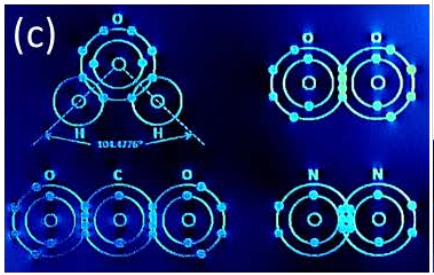


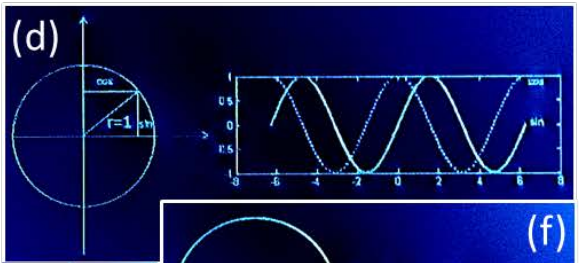
Coincidently, the lamella structures of ULN fused quartz and shocked quartz are similar

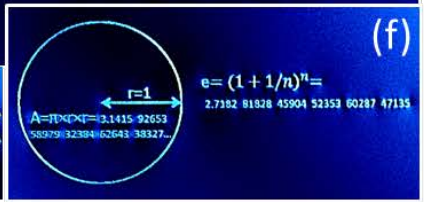
Southampton time capsule in quartz glass

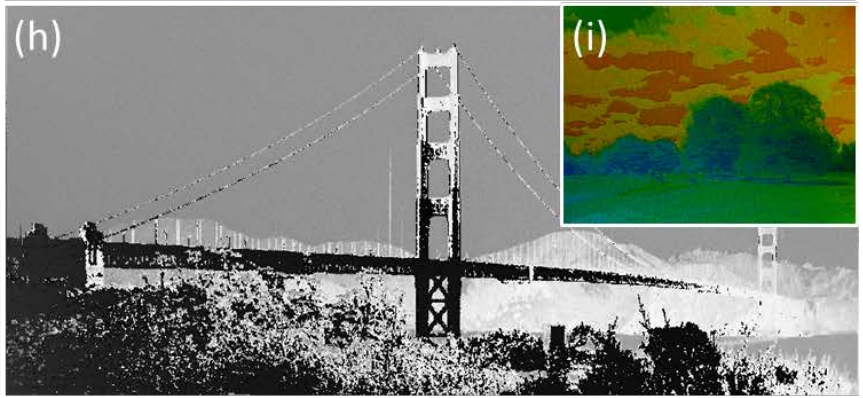












Conclusions

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

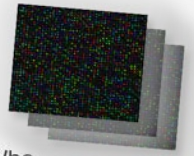
- For the first time, storage technology might allow human knowledge to outlive us.

OFFICIALLY AMAZING™

EXPLORE RECORDS | SET A RECORD

Most durable digital storage medium

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.



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Who

JINGYU ZHANG, MARTYNAS BERESNA, PETER G KAZANSKY, MINDAUGAS GECEVICIUS

What

300 QUINTILLION YEAR(S)

Where

UNITED KINGDOM
SOUTHAMPTON

When

23 JANUARY 2014

CUTTING-EDGE SCIENCE

First rocket-landing on Earth after deploying a payload in orbit

On 22 Dec 2015, SpaceX successfully landed the first stage of its *Falcon 9* rocket at Cape Canaveral Air Force Station in Florida, USA. The rocket had been launched the day before and had deployed 11 satellites into Earth orbit. The *Falcon 9* reached an altitude of 200 km (124 mi), after which the rocket's second stage took its payload of satellites into orbit. The first stage, which is 47 m (154 ft) tall, returned under its own power and landed vertically. The full journey is illustrated in this time-lapse photo.

DID YOU KNOW?
The VSV-EBOV (Vesicular Stomatitis Virus-Ebola Virus) vaccine was first developed at the National Microbiology Laboratory in Winnipeg, Canada, in 2005. Trials began on 23 Mar 2015. As of Aug 2015, more than 4,000 people who had had close contact with Ebola patients had been treated.

Most atoms quantum-entangled
On 26 Mar 2015, scientists from the Massachusetts Institute of Technology (USA) and the University of Belgrade (SRB) announced that they had quantum-entangled 2,910 atoms of rubidium (give or take 190 atoms). They achieved this by trapping the super-cooled particles between two slightly transparent mirrors and bombarding them with weak laser pulses.

Quantum entanglement occurs when particles are so fundamentally connected that they can theoretically influence each other – even across vast distances.

Shortest pulse of visible light
Scientists have created a light pulse lasting for just 380 attoseconds. One attosecond is a quintillionth (10^{-18}) of a second. The feat was achieved by Eleftherios Goulielmakis (GRC/DEU) and his team of researchers at the Max Planck Institute of Quantum Optics in Garching, Germany, and published on 4 Feb 2016.

Largest known prime number
On 7 Jan 2016, a computer volunteered by Dr Curtis Cooper (USA) at the University of Central Missouri, USA, discovered the Mersenne prime number $2^{74,207,281}-1$. The number has a designation M74207281. Reading two digits per second, it would take more than 100 days to read out the 22,338,618-digit number.

First effective Ebola vaccine

The experimental vaccine VSV-EBOV has been trialled in Guinea with a success rate of at least 75% and possibly far higher. The results of the vaccine trials were published in the journal *The Lancet* on 31 Jul 2015. The first recipient of the vaccine was Mohamed Soumah of Guinea (above); he was given the all-clear three months later.

FIRST DETECTION OF GRAVITATIONAL WAVES

Albert Einstein proposed the existence of gravitational waves in 1916, but they were not detected until 11 Feb 2016. They are made when huge objects in space speed up or slow down. By mapping the movements of these waves scientists have a new way of analysing signals from the universe. The detection was made by the LIGO Scientific Collaboration and the Virgo Collaboration using the Laser Interferometer Gravitational-Wave Observatory (LIGO).

LIGO is the **largest gravitational-wave detector**. It is located at two sites in the USA: Hanford in Washington and Livingston in Louisiana (below). Each houses two L-shaped, 4-km (2.5-mi) steel vacuum tubes, down which lasers are fired. The lasers interfere with each other in detectors, allowing tiny fluctuations in space-time to be studied, a process called interferometry.

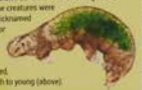
DID YOU KNOW?
[illegible]

1978 **Most Tour de France stage wins**
Eddie Merckx (BEL) celebrates his 34th stage win in the Tour de France. His first had come in 1969. Along with three other riders, Merckx also shares the record for the **most Tour de France wins** (5), with victories in 1969–72 and 1974.

FAST FACTS
When cooled to absolute zero (-273.15°C, -459.67°F), helium becomes a liquid that flows against gravity • Scientists have developed a way of recharging mobile phones with urine • We share some of our DNA with bananas

Longest time for tardigrades to survive frozen in ice

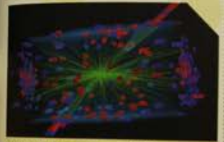
A tardigrade is a highly resilient, microscopic, eight-legged aquatic invertebrate. On 25 Dec 2015, scientists from Japan's National Institute of Polar Research announced that they had revived two adult tardigrades that had been frozen in water ice since Nov 1983. Also known as "water bears" owing to their appearance (above), the creatures were thawed in Mar 2014. Nicknamed SB-1 and SB-2 (short for "Sleeping Beauty"), they began moving after they defrosted. Only SB-1 fully recovered, but went on to give birth to young (above).



Most durable digital storage medium

According to results published on 23 Jan 2014, nanostructured glass made by researchers from the University of Southampton's Optoelectronics Research Centre, UK, can remain stable at room temperature for 300 quintillion years. At 188.9°C (371.9°F), it has an estimated lifetime of 13.8 billion years (roughly the current age of the universe). Data is written to the glass as three layers of nanostructured dots using an ultrafast femtosecond laser, giving a storage capacity of 360 TB (terabytes) per disc. For comparison, the text content of the entire Library of Congress is equivalent to 20 TB.

DID YOU KNOW?
[illegible]



Highest-energy ion collisions in a particle collider

On 25 Nov 2015, scientists using the Large Hadron Collider at CERN in Geneva, Switzerland, announced that they had collided two beams of lead ions together at 1,045 teraelectronvolts (TeV). This measurement is the energy equivalent to that of a bumblebee striking your face.

First spacecraft to orbit a comet
On 6 Aug 2014, the European Space Agency's *Rosetta* spacecraft entered orbit around comet 67P/Churyumov-Gerasimenko (67P). On 12 Nov 2014, it released *Philae*, a lander designed to analyse the comet's surface. As of 27 Jan 2016, *Rosetta* had been orbiting 67P for 539 days, and is the **longest orbital survey of a comet**.

Most distant object in the universe
Using data from the Wide Field Camera 3 on the *Hubble Space Telescope*, a team of astronomers announced on 3 Mar 2016 their discovery of a galaxy in the Ursa Major constellation. The light detected by *Hubble* from this galaxy, GN-z11, dates back 13.4 billion years, around 400 million years after the Big Bang. In that time, the expansion of the universe means that GN-z11 is now some 32 billion light years from Earth.

Longest X-ray free-electron laser
Located in Germany, the European XFEL stretches 3.4 km (2.1 mi) and across three research sites. This X-ray free-electron laser (XFEL) incorporates high-speed electrons moving through magnets. The laser itself measures 2 km (1.2 mi) long, with an acceleration length of 1.7 km (1.06 mi). It requires 17.5 billion electron volts and operates at a temperature of -271°C (-455.8°F).

First object 3D-printed from extraterrestrial material

On 6 Jan 2016, at the Consumer Electronics Show in Las Vegas, Nevada, USA, Planetary Resources and 3D Systems (both USA) revealed a 3D-printed model of a spacecraft part made from meteorite metals. The feat is a successful proof of concept that should allow future missions into the Solar System to create equipment and parts from asteroids.

Oldest person to get divorced **1980**
On 21 Nov, after nine years of marriage, 101-year-old Harry Bidwell of East Sussex, UK, divorces his 65-year-old wife, Lucy. He feels that she "wasn't domesticated enough" and is soon seeking a new partner.