Optics challenges in atom-based QT Sensors

Prof. Kai Bongs, University of Birmingham
Zeiss Symposium “Optics in the Quantum World”
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UK National Quantum Technologies Programme

- A **five-year £270M (now £380M)** programme announced by the UK government in 2013.
- Programme started October 2014.
- To exploit the potential of quantum science and develop a **portfolio of emerging technologies** with the potential to benefit the UK.
- Industry, government and academia working together to create opportunities for **UK wealth creation**.

Slide: Courtesy of D. Delpy
The UK Quantum Technology Hubs

- £120M Investment by EPSRC
- 132 partner companies

Projects:
- QUANTIC
  - PI: Miles Padgett
  - University of Glasgow
- QCH
  - PI: Tim Spiller
  - University of York
- NQIT
  - PI: Ian Walmsley
  - University of Oxford

Kai Bongs
University of Birmingham

Tim Spiller
University of York

Miles Padgett
University of Glasgow

Ian Walmsley
University of Oxford

David Delpy
Chair of UK QT Strategic Advisory Board
What we do: Atoms manipulated by laser light

Also possible: rotation, time, magnetic fields, …
Hub Strategy
“Disruptive Innovation Triangle”

Technology Research

Research to Demonstrate Benefits

User Challenges

UK National Quantum Technology Hub Sensors and Metrology
Hub Strategy

Supply chain Components & subsystems

Technology Research

Research to Demonstrate Benefits

Applications

Engage the whole Industrial VALUE CHAIN

End-User Systems

User Challenges
Roadmaps towards £3bn market opportunity

Atoms sensing

- GRAVITY GRADIENTS £1bn
- TIME £500M
- MAGNETIC FIELD £1bn
- ROTATION £500M
- THz £400M
- making QUANTUM LIGHT £100M

Atoms based QT platform

UK National Quantum Technology Hub
Sensors and Metrology
Hub-Related UK QT Ecosystem

- 77 collaborative projects with industry
- 43 industry partners
- £50M project value
- 50 jobs in industry
- 9 patent applications
- 132 Records of invention
Accelerometer Operation
Why Cold Atom Quantum Technology?

- Already outperform classical counterparts
- Huge scaling potential (1000 x better)
- Free of mechanical wear
- Absolute – i.e. long term stability
- Excellent common mode rejection as gradiometer
Miniature Standardised Cold Atom Systems

Laser Systems

Grating-MOT

Miniature Vacuum

3D printed coils

University of Glasgow

M Squared

Compound Semiconductor Technologies

IQE

Optocap

University of Strathclyde

Fraunhofer UK

680nm VCSEL

VCSEL chip

680nm VCSEL fiber

Laser on PET

University of Strathclyde

M Squared

University of Southhampton

TELEDYNE E2V

The University of Nottingham

3D printed magnetic shields

ADDED SCIENTIFIC

University of Birmingham

Magnetic Shields

Electromagnetic Engineering
Demonstrators
Market Example WP11: QT Gravity Gradient Sensors for Underground Mapping

UK cost of digging up the roads: £5bn/yr
Functional Brain Imaging

Functional brain imaging currently requires patients to remain still in a highly restricted environment. These conventional scanners are limited in sensitivity, and some subject groups are excluded – particularly infants.

Next generation quantum sensors are allowing a step change in technology – a “wearable” neuroimaging system. Allows scanning of subjects of any age, with free head movement and better sensitivity and spatial resolution compared to conventional systems.
Electromagnetic Imaging with Atomic Magnetometers and Machine Learning


4 mm: Chosen spatial resolution of the imaging system (pixel size)
Quantum Sensor Roadmap

- **Laboratory demonstrations**
  - Size: room
  - Power: kW
  - Beating classical counterparts

- **Specialised QT sensors**
  - Car boot
  - 100s Watt
  - 10 x better than classical
  - Integrated components
  - New schemes

- **Industry QT sensors**
  - Backpack
  - 10s Watt
  - 100 x better than classical

- **Consumer QT sensors**
  - Handheld
  - Watt
  - 1000 x better than classical
  - Fully integrated systems
  - New schemes

- **2015**
  - Superposition
  - Laser cooling

- **2020**
  - Composite pulses
  - QND detection

- **2025**
  - Large momentum beamsplitters

- **2030**
  - Entanglement
  - QT sensor networks

- **Defence**
  - Geophysics

- **Medical diagnostics**
  - Construction
  - Naval navigation
  - Data storage masters

- **Health monitoring**
  - Gaming interfaces
  - GPS replacement
  - Data storage products
  - Local network timing
  - Gravity imaging

- **QT Sensor market**
  - £1bn
  - £100M
  - £10M

- **Fundamental research**

- **Hub activity**
Optics Challenges
Laser cooling

The Nobel Prize in Physics 1997
"for development of methods to cool and trap atoms with laser light"

S. Chu  C. Cohen-Tannoudji  W.D. Phillips

Laser linewidth and absolute frequency stability < MHz (<natural linewidth)
For red cooling transition in Sr <kHz !
How Quantum Sensors work: Gravity
Measuring Gravity

\[ k_z T^2 g_z = 2\pi \frac{\Delta z}{\lambda} \]

- Dropping object next to laser ruler
- Accuracy of 1 part in $10^{10}$ requires a 1 in $10^{10}$ accuracy in laser wavelength!!!
- Laser linewidth $< 10$ kHz
- Gravity gradiometers have similar requirements
- Also think of power!!!
Wavefront Effects

Detecting $10^6$ atoms delivers shot noise of 1 mrad or $\lambda/1000$

Using Entanglement would make this $\lambda/1000000$!
Optics Challenges

- Stable lasers – step-change in SWAP-C
- Robust optical delivery (polarisation in fibres vs complexity in free space)
- Low-loss integrated optical components (in particular µs, 100dB switches)
- Recycle optical power and stay frequency agile?
- Ultra-flat wavefront optics (inside or through vacuum)
  - Could I have those with flat intensity as well, please?