Programmable Quantum Optical Circuits using a Multi-mode Fibre

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1 Quantum Technologies for the UK

UK Businesses lost **£3.3 billion** to cybercrime in 2021-22

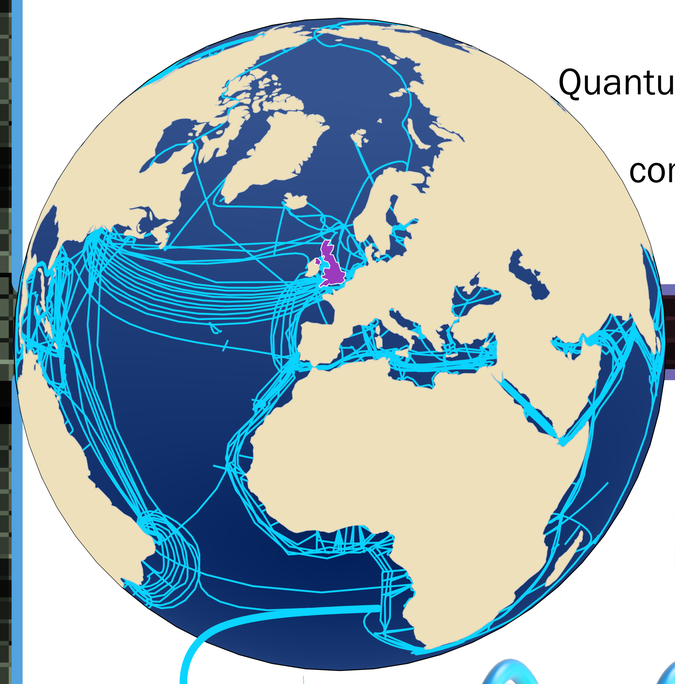
AI infrastructure in the UK will need upto **72 TWh** of electricity by 2030.

A GPS outage could cost UK upto **£1 billion** per day.

These seemingly unrelated problems have a common solution: **Quantum Technologies**

Quantum computing is est. to have ~**£50 billion** market share by 2035. This will impact energy infrastructure, drug discovery, climate sciences, and AI.

Quantum sensors can monitor greenhouse emissions, and replace GPS with unprecedented accuracy.

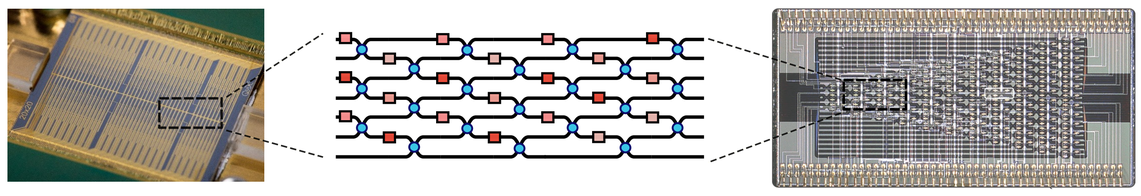


Quantum networks promise **unhackable data security** and secure communication via existing network of undersea optical fiber cables.

2 Optical Circuits and Challenges

Optical circuits lie at the epicentre of photonic quantum technologies, being fundamental for quantum computing, sensing and networks.

Conventional Circuit Design



Conventionally, these circuits are contructed with thousands of tiny components arranged in a prescise meshgrid structure.

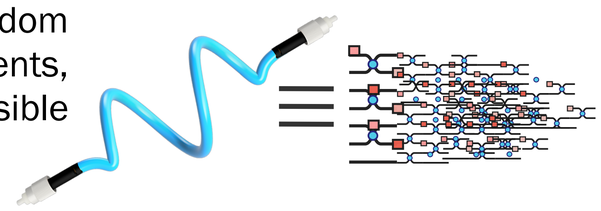
Limitations:

- ✕ Number of optical components scale poorly with the size of the circuit.
- ✕ Tiny fabrication errors lead to dramatic performance loss.

C. Taballione et al., Quantum 7, 1071 (2023). W. Bogaerts et al., Nature 586, 207–216 (2020)

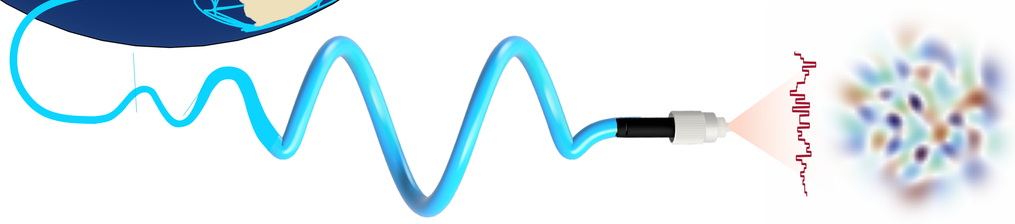
Multi-Mode Fibre based Design

A multi-mode fibre mimics a random arrangement of such components, embedding thousands of possible circuits within itself.

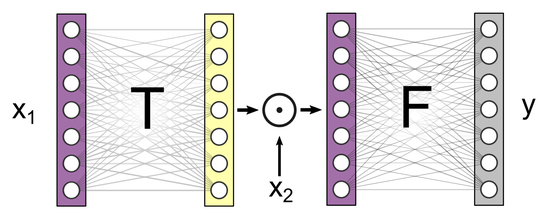


3 Putting Disorder to $\hat{U}$se

By virtue of its complexity, light coming out of a multi-mode fibre looks disordered

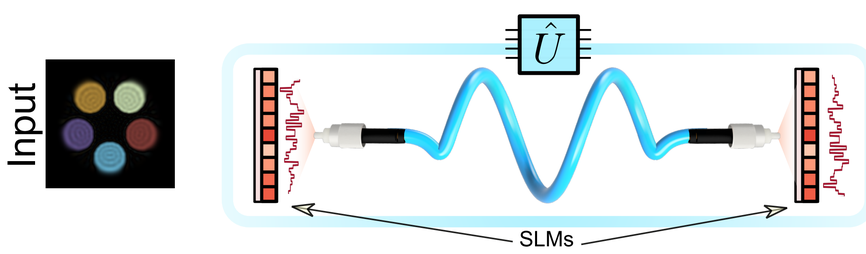


We used machine learning to characterise this disorder within a multi-mode fibre. With this knowledge, we can inverse design a desired optical circuit within it.

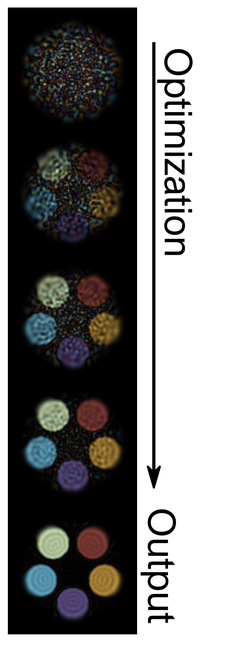


SG et al., Optics Express 31, 20 , 32824-32839 (2024)

We then place this fibre in-between a pair of spatial light modulators (SLMs), used to shape structured light.



By optimising the patterns displayed on the SLMs, we program a desired optical circuit $\hat{U}$ within the fibre

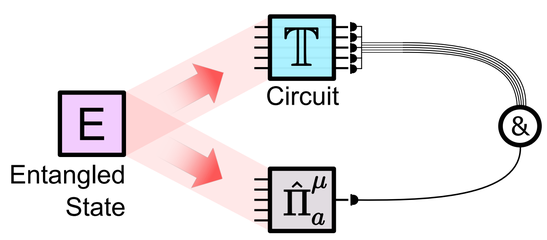


Y. Sakamaki et al., J. Light. Technol. 25, 3511–3518 (2007)

4 Results

1. We utilise this platform to implement various quantum gates to manipulate and measure quantum entanglement shared between a pair of photons.

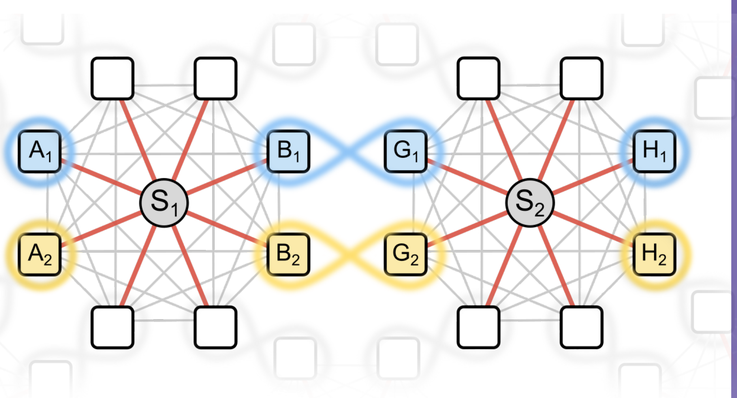
   Applications: quantum computing, quantum measurement, secure quantum communication.



Nature Physics *20, 232-239 (2024)*

2. We use such an optical circuit to route and teleport entanglement between two local quantum networks with four users each. This serves as a scalable path towards a global quantum network.

   Applications: quantum network, quantum internet.



arXiv:*2501.07272 (2025)*

5 Key Takeaways

- ✓ Quantum technologies will revolutionalize UK's economy, healthcare, infrastructure & research.
- ✓ Optical circuits, vital for quantum photonics, are difficult to fabricate scalably and precisely.
- ✓ We use an alternative design to program optical circuits using multimode fibres. This is scalable, robust to errors, with direct applications in quantum computing, sensing and networks.

Res #1 Res #2

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