QUANTUM INFORMATION

An integrated light circuit

Paul G. Kwiat

There's a long wish list for a workable quantum computer: a viable system must be fast, compact and stable. The first integrated optical quantum logic circuits are a step in the right direction.

Systems that use photons are one of several candidates for making a working quantum computer. One challenge (there are many) is to move beyond the current bulky experiments that involve just a few photons to the kind of stable, miniaturized circuits with very many logic gates that lie at the heart of conventional, classical computers. Writing in *Science*, Politi *et al.*[1] report how they have used integrated optics for the first time to demonstrate several primitive functions of quantum logic.

Quite generally, the promise of quantum computing lies in making use of the 'parallelism' and 'connectedness' of quantum-mechanical phenomena such as superposition (that objects can be in many states at once) and entanglement (that the properties of two objects can be tied to one another, despite being separated in space). These features can be used to solve information-processing tasks that would be impossible, or at least very difficult, for processors denied these quantum advantages[2]. Instances include problems related to factoring large numbers into their prime constituents (think $21 = 3 \times 7$, writ large); efficiently searching an unsorted database; and even hard problems in quantum mechanics. This last application might well end up being the most important of all, helping to form a robust framework for understanding future problems in science and technology.

How can quantum computers achieve such feats? At a basic level, every quantum processor is essentially a complex, interwoven web of nested interferometers in actual physical space (for optical approaches) or in some abstract space. An optical interferometer is made of mirrors and partially reflective, partially transmissive elements known as beam splitters. These are arranged into an optical obstacle course that an incident photon can traverse in two or more ways.

This multiplicity of paths (very) loosely corresponds to the parallel operation of a computer algorithm. By arranging elements in a certain way, one can construct logic gates for single quantum bits (qubits), preparing them in arbitrary superpositions of the logical 0 and 1. Other arrangements can entangle two qubits, so that the state of one is altered by the state of the other[3] (Fig. 1a).

To understand where Politi and colleagues' achievement fits in, we need first to consider classical interference effects. We see these, for example, in light reflecting off a puddle with oil in it. The colours we see depend on the direction in which we are looking, and in the details of the oil–water non-mixture (the effect depends on the varying thickness of the thin oil film lying on top of the water). This kind of swirling, shifting pattern is exactly what we don't want for a reliable computer. Experiments on quantum computing thus far have done a tolerably good job of controlling the analogous instability, and thus realizing basic quantum operations[4–6].

State-of-the-art processors for optical quantum computing currently use just six photonic qubits[7]. But the large-scale quantum algorithms of the sort we dream of running some day (or, at least, I dream of running) will require hundreds or thousands of stable, interconnected interferometers and low-loss, high-performance components. There are ways of correcting quantum-computational errors as they arise[8,9], but if they are to work properly, they require a high base-level of performance that would be nearly impossible to achieve on such a large scale. And quite apart from questions of reliability, there are also questions of speed and bulk. Just as we couldn't imagine running a modern computer application on an old-school processor that uses vacuum tubes — it would be far too bulky and slow — the complex, scaled-up quantum computer of tomorrow will require a more integrated approach[10].

Enter Politi and colleagues[1], with their first stab at quantum-logic operations in an (optical) integrated circuit (Fig. 1b). They succeed in replacing the bulky mirrors and protracted path lengths of traditional experiments by micrometre-scale optical waveguides — pipes for light — fabricated into a silicon wafer. Much as fibre-optic cables guide light in modern telecommunications applications, these waveguides direct the photons along their desired trajectories — rather like an irrigation system to deliver photons where and when you need them.

Such integrated optical circuits are smaller and cheaper than bulk-optic systems (or at least they will be once we have settled on an optimized design and fabrication). They are also inherently more stable; temperature variations that could alter the finely balanced path lengths in particular areas of a chip tend to cancel out. In addition, once in the waveguides, photons tend to go only where they should, so there are no optical paths to align, as there are in conventional optics. Politi *et al.* demonstrate high-quality classical and quantum interference with their system, as well as basic one- and two-qubit logic, and entanglement with better than 92% fidelity. Their results are both a significant and a necessary step towards optical quantum computing.

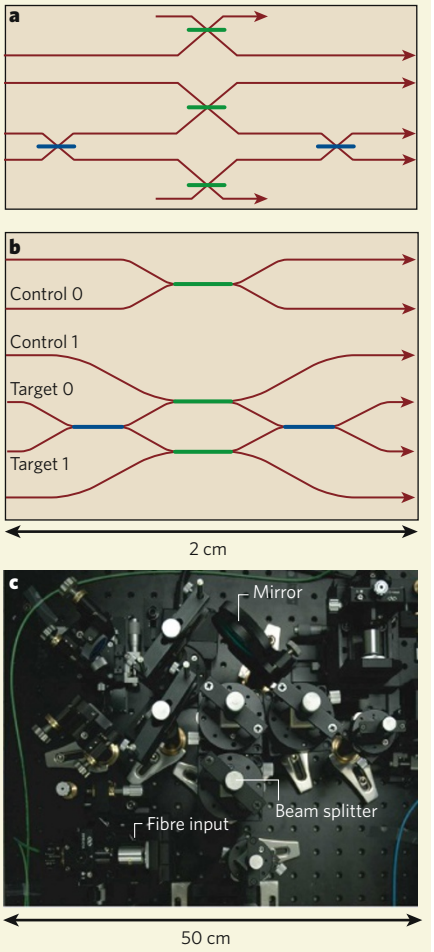

Figure 1 | Light circuits. a, This circuit represents a basic two-qubit quantum logic gate. Blue beam splitters reflect 50% of the incident light, green beam splitters 33%. In this configuration, a combination of quantum and classical interference flips the target qubit states 0 and 1 if the control qubit is a 1. **b**, Politi and colleagues' first implementation[1] of this scheme as an integrated optical circuit uses silica-on-silicon waveguides. **c**, A bulk-optics implementation of a circuit of similar complexity involves various mirrors, beam splitters and fibre inputs; the result is considerably bigger and less stable.

Lest the reader gain an unhealthily rosy perspective, significant challenges must still be faced. There is much less opportunity to adjust these integrated circuits once they are fabricated — there is nothing to be twiddled with, unlike in conventional optical systems (Fig. 1c) — and so their design must be optimized very carefully. In addition, low-loss interconnects are a must: at present, the efficiency with which light is injected into and extracted from the circuit is 60%. That is good, but not great, and low enough to make the 99% transmission rate inside the device significantly less meaningful.

Outside the integrated circuit, other components also require work before we can achieve

large-scale quantum computing using light. For a start, we need high-quality, on-demand sources of single and entangled photons, along with a low-loss device in which to store them. Then we need photon detectors of very high efficiency (so much the better if they can actually count the number of incident photons). All of these problems are currently being attacked by various research efforts around the world. Stay tuned for more big news from tiny circuits. ■

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TUBERCULOSIS

Deadly combination

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Many factors affect the severity of tuberculosis in infected individuals. Among these are the genetic make-up of the bacterial strain, that of the host, and the interplay between the two.

A quick scan through this article might take five minutes of your time. During this period, 16 people will have died of tuberculosis, 80 will have fallen ill with it, and an astounding 800 will have become infected with the disease-causing pathogen *Mycobacterium tuberculosis*[1]. Yet, with only 1 in 10 of those infected developing tuberculosis in their lifetime, clearly most humans control the infection effectively. It is well known that resistance to tuberculosis depends on complex interactions among the host, the bacterium and the environment or culture. But the relative contributions of these factors, and the relationship between them, remain unclear. Work by Caws and colleagues[2], published in *PLoS Pathogens*, is a first attempt at revealing the genetic contribution to interspecies communication between *M. tuberculosis* and its human host.

When bacteria reach human lungs — borne by tiny droplets from a cough or sneeze — they are usually engulfed and destroyed by the macrophage cells of the immune system. But *M. tuberculosis* has developed mechanisms to survive these assaults.

Detection of this pathogen by the pattern recognition receptor TLR-2 on the surface of macrophages (Fig. 1) induces a signalling cascade mediated by the TLR-2 adaptor protein TIRAP. Total activation of these primed macrophages is effected by soluble immune mediators, particularly IFN-γ, which is secreted by white blood cells known as T cells[3]. Fully activated macrophages fail to eradicate *M. tuberculosis*, but restrict its growth[4]. Consequently, the infected individual develops latent tuberculosis, remaining healthy while harbouring dormant bacteria.

Unfortunately, the pathogens can be resuscitated if the immune response diminishes, leading to pulmonary tuberculosis — the form of the disease that is confined to the lung and accounts for 80% of cases. When the bacteria reach the bronchial tree during active disease, the host becomes contagious. And once they infiltrate the bloodstream they can be dispersed to other organs. Meningeal tuberculosis, which affects the brain, is the most common (forming up to 30% of all cases) and the most hazardous form of extrapulmonary disease.

As early as the nineteenth century, it was assumed that genetic disposition contributes to the host's susceptibility to tuberculosis, but only recently were several culprit genes identified. These genes can be divided into two groups according to whether they contribute to acquired or innate immunity. Mutations in genes involved in acquired immunity, such as the IFN-γ-mediated signalling pathways[3], are relatively rare but invariably lead to mycobacterial disease on infection — usually early in life. Genes modulating innate immunity operate more subtly, through natural genetic variations (polymorphisms), in both a synergistic and an antagonistic way. Examples of such genes include those encoding TLR-2 and TIRAP.

Polymorphisms are also rife among the different strains of *M. tuberculosis*. Different lineages of this bacterium exist that may have co-evolved in close relationship with a specific host population[5]. Also, separate bacterial families have developed within lineages. The Beijing family of the East Asian lineage, notorious for causing multidrug-resistant tuberculosis and spreading globally, is a noteworthy example.

Caws *et al.*[2] analysed polymorphisms both in Vietnamese adults with pulmonary or meningeal tuberculosis and in *M. tuberculosis* strains isolated from these patients. Their observations are consistent with most, although not all, previous work linking[6–9] polymorphisms in TLR-2/TIRAP with susceptibility to tuberculosis within the same and different ethnic groups in West Africa and Turkey. They report a close relationship between polymorphisms in the gene encoding TLR-2 and susceptibility to infection with the Beijing strain of bacterium. One particular TLR-2 polymorphism probably fails to mediate the full priming of macrophages, rendering individuals carrying it more susceptible to infection. The combination of a defective TLR-2 response and infection with the virulent Beijing strain is especially problematic, as it may increase the risk of extrapulmonary dissemination and

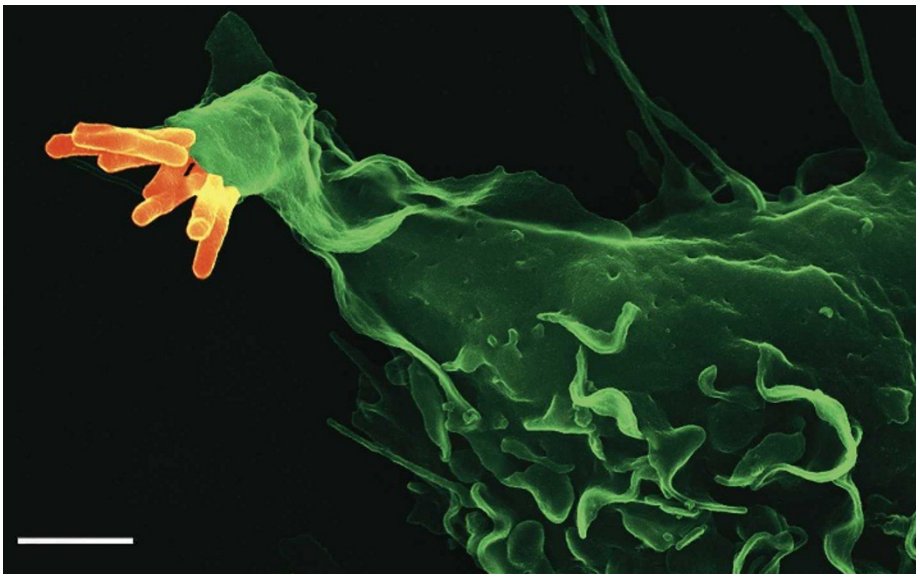

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Figure 1 | Host and pathogen. On reaching the host's lungs, cells of *Mycobacterium tuberculosis* (orange) bind to the TLR-2 receptor on the surface of a macrophage (green). Caws *et al.*[2] speculate that polymorphisms both in the host genes (those encoding TLR-2 and its adaptor protein TIRAP) and in bacterial virulence factors (PGL and the DosR complex) affect the severity of tuberculosis. (Scale bar, 2 μm.)