probability of this quantum receiver did not fall below 10^{-4} is due to experimental limitations; in particular, the visibility of the interferometer at the beamsplitter used in the displacement operation and the detection efficiency of the single-photon detector were major sources of imperfection. Imperfect visibility causes errors in photon counts even when a correct displacement operation is carried out, and imperfect detection efficiency causes false negatives in photon counting for some signals displaced into the non-vacuum state. Nevertheless, by employing forward error correction methods used in conventional communication systems, the error rate of 10^{-4} can be reduced to a nearly error-free state. This suggests some challenges for the future, including the construction of a local oscillator required for the displacement operation. Of course, other improvements may also be needed, such as speeding up the operation of the required feedback loops and field-programmable gate array technology, downsizing the size and mass of the receiver, and developing faster single-photon detectors. Moreover, if this experiment is to be conducted outside of a laboratory environment, errors caused by background light must be taken into account. ❐

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PHOTONIC CRYSTALS

Turning data on a dime

By enlisting help from a robot to assemble precise structures, researchers have guided telecommunications-wavelength light around multiple hairpin turns in a three-dimensional photonic crystal.

Peter Bermel

Long-haul fibre-optic telecommunications systems are the backbone of the Internet and offer significant advantages for data transmission in terms of energy use, speed, capacity and distance. However, over shorter distances, such as for a computer cluster filling up a room, an office network or a computer motherboard, alternative technologies like copper wires and radiofrequency transmission dominate, owing to their greater flexibility. As a result, in recent years there has been a great deal of interest in improving the flexibility and usefulness of short-haul optical communications, in order to achieve the best of both worlds.

Now, writing in *Nature Photonics*, Ishizaki *et al.* report the first demonstration of arbitrary selective guiding of unpolarized telecommunications-wavelength light around multiple sharp bends[1] using three-dimensional (3D) photonic crystals[2]. Their woodpile-based 3D photonic crystals confine light to narrow waveguides with a large 3D photonic bandgap — a range of optical wavelengths in which no angle or polarization of light can escape. The assembly of woodpile structures is easier to fabricate than many traditional 3D photonic crystal designs, as it can be performed one uniform layer at a time by a robot that automates the assembly process. This automation is particularly helpful in aligning each successive layer in order to achieve 3D periodicity. The woodpile structure includes line defects in both horizontal and 45° vertically tilted directions to guide the light where it is wanted. It is worth noting that this combination of junctions facilitates mode matching; this is an improvement on previous efforts, in which the vertical waveguide modes experienced vastly different dispersion from the horizontal waveguide modes[3]. The researchers established coupling rules for best-matching horizontal–horizontal, horizontal–oblique and oblique–oblique combinations, based on physical intuition and finite-difference time-domain simulations. They then fabricated and characterized not only basic 3D woodpiles with full 3D photonic bandgaps in the range of 1,220–1,450 nm, but also a series of increasingly complex waveguide structures linked together. In their most striking results, the incident light was split and routed to two separate outlets on opposite sides of the crystal[1].

To appreciate fully the significance of these results, it is helpful to review the historical development of information transmission technology. After the invention of the telephone in 1876, engineers began using metallic wires to transmit information efficiently without interference. In 1966, Charles K. Kao theoretically described a method capable of transmitting more information over longer distances: namely, sending light over ultralow-loss glass fibres, known as fibre-optic cables[4]. Within four years, a team at Corning Glass Works had built, tested and patented a fibre-optic cable theoretically capable of transmitting 65,000 times the amount of information carried by copper wires[5]. However, a complete system for transmitting information required two other essential elements: a relatively inexpensive light source amenable to rapid modulation, and an optical receiver at the same wavelength as the source. The light source problem was fortuitously addressed the same year with the invention of a semiconductor diode laser capable of continuous-wave operation at room temperature[6]. The receiver problem was solved by using silicon photodiodes, which had already been employed for use in photovoltaic cells. By 1976, fibre-optic systems were beginning to be deployed for commercial use. However, there was a catch: despite the enormous improvements that had been made, reductions in fibre-optic losses were still limited, particularly in the 800–900 nm range. To extend the range of telecommunications across long distances, another innovation came into play: erbium-doped fibre amplifiers, which allowed researchers to strengthen and repeat a complex optical signal over thousands of miles[7]. This was successfully demonstrated for trans-Atlantic optical data transmission in 1988. Fibre-optic communication now accounts for the vast majority of global data transmission, making it a remarkable success[8]. Successive improvements to this technology, such as the increasingly dense utilization of neighbouring wavelengths and polarizations, have enabled internet traffic to rise at an compounded annual growth rate of 40–50% over the past decade[9].

Recently, several research groups have been exploring whether any of the successes in long-haul fibre-optic telecommunications can be adapted to improve the performance of short-haul high-bandwidth applications, including high-performance computing and data centres. The broad field of silicon nanophotonics offers a promising way to achieve high-performance optical connections[10]. In this approach, complementary metal–oxide–semiconductor (CMOS)-compatible fabrication processes are employed to produce optical components that vertically interconnect with a conventional electronic layer. Much like in long-haul telecommunications, key optical components include optical sources and passive waveguide components (analogous to fibre-optic cables). At a higher level, novel challenges are posed by the packaging and assembly of nanophotonic systems with other subsystems, potentially including electronic, micromechanical and microfluidic systems, and the integration of heterogeneous materials such as group III-V compounds, quantum dots and nanoplasmonic materials. Given the likelihood that tightly spatially constrained and multifunctional systems will see rapidly increasing adoption in the future, being able to make light follow a potential complex path in three dimensions with low losses will be essential for successful deployment and scaling.

The recent work of Ishizaki *et al.* is particularly important because of the experimental fabrication and characterization techniques employed. The researchers constructed 3D woodpile photonic crystals from earth-abundant silicon, which they precisely aligned and stacked to include the air gaps required to create the largest photonic bandgap and lowest loss for a modestly sized structure. Their alignment and stacking system, which utilizes automatic pattern recognition to decrease errors, seems to be the most advanced in the world. The proof is in the pudding, of course, and all the scanning electron microscopy images look precisely as they should. The researchers measured the optical transmission of the system by focusing a 1.55 μm monochromatic Gaussian beam on the entry port, defocusing at the expected exit port, and comparing these to a control experiment in which the 3D photonic crystal was not present. The

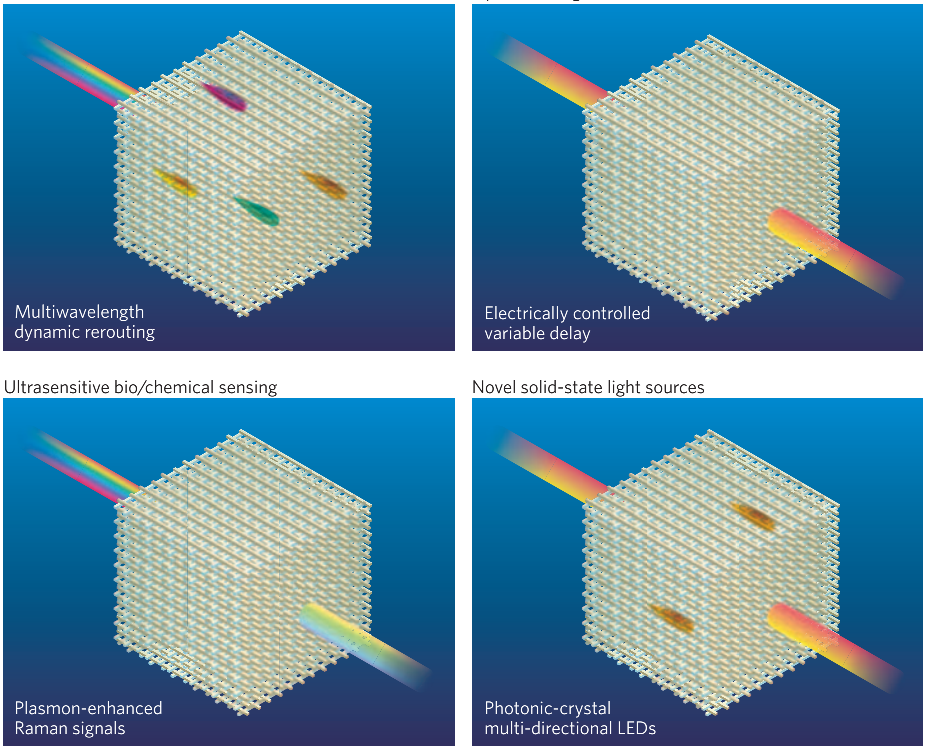

Figure 1 | Potential new functionalities enabled by high-performance nanophotonic light guiding, including ultrafast data transmission, optical storage, ultrasensitive bio/chemical sensing and novel solid-state on-chip light sources.

results, although noisy, seem reasonable compared with back-of-the-envelope estimates and preliminary simulations that one might perform for such a system. Although the absolute percentage of transmission is not high (currently in the range of 0.01–1%), it seems to be sufficient for data transmission applications, and could be systematically improved in future work.

On the other hand, possibly due to space limitations, Ishizaki *et al.* did not address a number of key issues as precisely as they have done in previous work[11]. In particular, questions about the sensitivity or preservation of polarization for these particular waveguide structures, and general principles for designing appropriate horizontal–vertical waveguide interconnects, are not discussed; the reader is well-advised to consult ref. 11 for more details on this topic. Furthermore, the experimental results lack any direct theoretical calculations. Even if *ad hoc* assumptions were used to achieve an approximate match, they would add a great deal of insight into what works well and what needs to be improved in the experimental structures fabricated so far. This task will be critical if the approach of Ishizaki *et al.* is to be extended to more complex optical circuitry, because problems such as back reflection can multiply rapidly with the complexity of the circuit.

Further theoretical and simulation studies are needed to complement the findings of Ishizaki *et al.* Investigation of usability over a selected, tunable range of wavelengths would be appropriate for enabling wavelength-division multiplexing applications, which can be used to subdivide channel capacity at the optical link level. Additionally, an exploration into the new functionalities that could be uniquely enabled by this photonic platform, including optical storage, ultrafast data transmission, photonic crystal surface-emitting lasers and nanoplasmonic miniaturization incorporating various novel materials, as illustrated in Fig. 1, would seem to be warranted. Perhaps this work will pave the way to the emergence of a viable alternative to conventional fibre-optic approaches, finding particular value wherever space is at a premium. ❐

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MICROSCOPY

Label-free nanoscopy of living cells

A holographic microscope capable of dynamically imaging unstained living cells at resolutions beyond the diffraction limit could prove extremely useful for studying biological cells.

Gary Brooker

Researchers at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland have made a significant step towards the realization of optical methods capable of imaging living biological structures at resolutions beyond standard optical limits. Writing in *Nature Photonics*[1], Cotte *et al.* describe a clever technique that combines holographic phase microscopy[2] with optical and computational concepts previously used to break the diffraction barrier[3–5]. In this new approach, image resolution is boosted to approximately twice the Rayleigh or Abbe optical limit, reaching about 70 nm with a ×63, 1.4-numerical-aperture oil-immersion objective. An important advantage of the scheme is that it is capable of monitoring the dynamics and structure of living cells without fluorescent marker dyes. Although the method requires the sample to be illuminated with laser light, it is less phototoxic to cells than other super-resolution methods because the intensity of light is much lower than that required to excite fluorescent dyes. In addition, because this technique does not rely on fluorescent labels, there is no risk of indicator dyes interfering with normal cellular processes.

The result is a scheme that offers the potential for long-term non-toxic imaging of dynamic cellular processes at high resolution. Cotte *et al.* present a particularly impressive example that demonstrates the capabilities of their technique: high-resolution images of neurons growing and making synaptic contact over a period of about an hour, recorded on a minute-by-minute basis. This type of temporal and spatial resolution will be very useful for many studies of biological cells. In other experiments, they confirmed the enhanced resolution of the microscope with images of *Escherichia coli* and diatoms.

This new device, which the researchers call a '2π digital holographic microscope' (2π DHM), relies on a significant modification to their original DHM[2]. The sample is positioned between two identical high-numerical-aperture oil-immersion objectives, positioned above and below the sample by a distance exactly equal to their focal length. This optical path forms one arm of a Mach–Zehnder interferometer set-up, with the other being the reference path. Blue (405 nm) light from a diode laser is split into sample and reference beams, with the sample beam illuminating the sample through the top objective lens at a very steep angle. A hologram is recorded on a digital camera by combining the beam that has passed through the sample and bottom objective lens with the reference beam. The beam is then rotated by a small angle and the process is repeated, with one hologram recorded for each beam position.

The improved image resolution is achieved by employing synthetic aperture and multiple viewpoint holographic methods. After the holograms have been captured, high-resolution images of each plane in the sample are created by applying extensive computer processing, including Fresnel propagation, image stitching and custom methods of image deconvolution. The results, when compared with the standard phase digital holographic method, show a compelling enhancement in resolution.

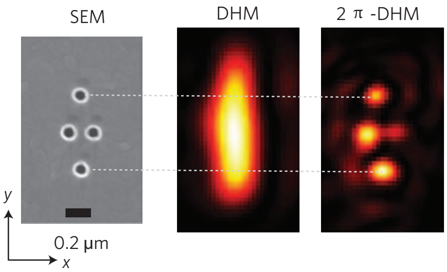

Figure 1 | A reference standard with 70 nm holes, confirmed by scanning electron microscopy, cannot be resolved by a standard DHM, but can be resolved using the new super-resolution 2π DHM developed by Cotte *et al.*

Cotte *et al.* quantified the resolution performance of their 2π DHM system by using it to image a standard sample — an array of 70 nm holes, each spaced by 70 nm — created at the EPFL's Center of MicroNanoTechnology. They then benchmarked the results against a scanning electron microscope, which confirmed the exact size and placement of the holes. When imaging the sample with their new 2π DHM, the researchers demonstrated that it does indeed provide 70 nm resolution, whereas their standard DHM failed to resolve these small structures (Fig. 1).

There are always drawbacks to every method, and, despite the many advantages of the 2π DHM, it does have some limitations. The first is specificity. This method could indeed be very useful if the overall shape and movement of a cellular structure needs to be determined. However, as the method does not image specific tagged structures, it lacks the specificity that other super-resolution methods can achieve, which often utilize a myriad of fluorescent dyes and proteins to monitor specific intracellular processes.

A second issue is phototoxicity, which arises owing to the use of blue light with a wavelength of 405 nm. Although the light is not particularly intense, this short wavelength is more phototoxic than longer wavelengths in the visible or infrared. The researchers probably selected a shorter wavelength to maximize resolution, as the physical laws of optics dictate that resolution worsens as wavelength increases. However, the principles of the 2π DHM system are potentially compatible with any wavelength and there is no reason why the scheme couldn't be applied to visible or infrared wavelengths (with a predictable