applications of deterministic single-photon extraction do not require pure states, such as photon-number-resolving detectors, as well as many protocols of quantum cryptography and quantum information processing.

Altogether, this experiment is clearly a significant step forward for quantum optics, but to become practical and suit widespread use the system ideally needs to be further integrated and miniaturized. One possible strategy for achieving this could be coupling the emitter to smaller planar resonators[7] or integrating the atom-cooling set-up onto the chip[8]. Another direction could be to use solid-state quantum emitters of photons, such as quantum dots[9] or defect centres[10]. ❐

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MICROWAVE PHOTONICS

# The programmable processor

Reconfigurable optical chips made from 2D meshes of connected waveguides could pave the way for programmable, general purpose microwave photonics processors.

José Capmany, Ivana Gasulla and Daniel Pérez

The emergence of new communication applications, such as 5G wireless systems, smart cities and the Internet of Things, will call for a new paradigm in the design of access networks[1]. In particular, future wireless networks will need to satisfy two fundamental requirements. First, the need to accommodate unprecedented data bit rates per end user (for instance, 5G targets up to 10 Gb s$^{-1}$ per user). Second, they will need to cope with an ever-increasing number of simultaneous wireless connections, for instance man–man, man–machine and machine–machine communications[2]. Addressing these challenges necessitates the use of radiofrequency carriers with higher frequencies and smaller coverage cells (that is, pico- and femtocells) serviced by base stations with smaller antennas. It will also require the extension of the photonic segment of the network (that is, optical fibre plant) into wireless base stations. A key to success will be the realization of a smooth interface between the radio and the photonic parts of the access network[1,2]. Microwave photonics[3] (MWP) is the natural option for this interface. It enables the generation, processing and distribution of microwave and millimetre-wave signals by optical means, benefiting from the unique advantages inherent to photonics, such as low loss, high bandwidth and immunity to electromagnetic interference.

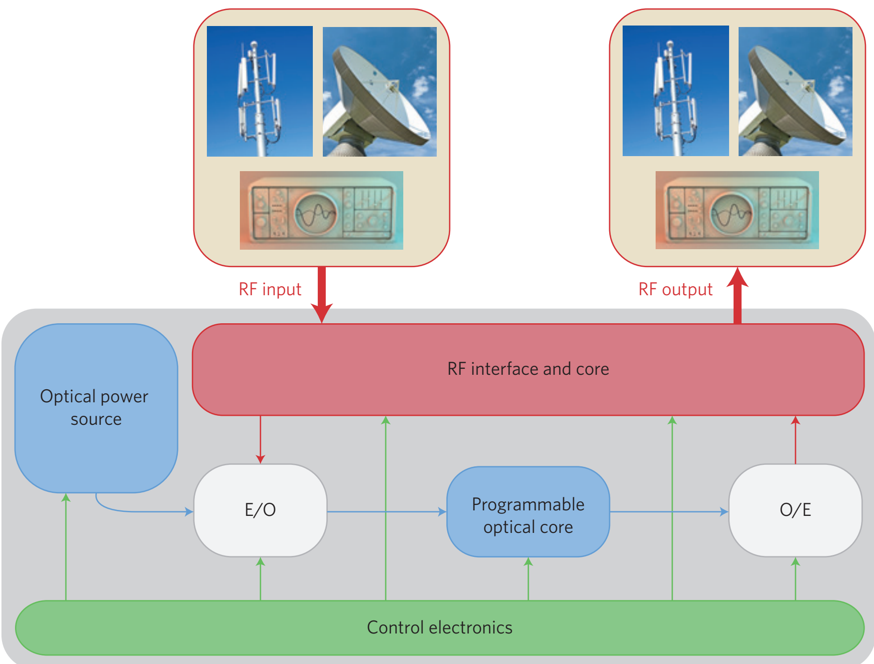


**Figure 1 |** Generic concept of the universal integrated microwave photonics processor. RF, radiofrequency. E/O is electrical-to-optical conversion and O/E is optical-to-electrical conversion. All images from Thinkstock: antenna, swisshippo/iStock; satellite dish, Zoonar RF/Zoonar; oscilloscope, kanishiotu/iStock.

Until recently, applications for MWP systems have been limited by the high cost, bulky size and power hungry nature of such systems. The emergence of integrated microwave photonics[4] (IMWP) circuitry is changing this situation by integrating MWP components and/or subsystems in miniature monolithic or hybrid photonic circuits. IMWP has the potential to change the power scaling laws of high-bandwidth systems through architectures that combine photonics with electronics to optimize performance, power, footprint and cost. IMWP has focused so far on the so-called application specific photonic integrated circuits (ASPICs), where a particular circuit is designed to perform a specific MWP function. This trend is leading to fragmentation, where the number of technological solutions almost equals the number of required applications.

A radically different approach is to design a universal MWP signal processor[5] that can be integrated on a chip and programmed to perform a variety of functions. This concept is inspired by field-programmable gate arrays (FPGAs) in the world of electronics, where a common hardware platform, or processor, is reconfigured by software to perform a multitude of tasks. Such a processor should bring greater flexibility and reductions in space, weight, power and cost compared with existing ASPICs. Only three material platforms — indium phosphide (InP), silicon-on-insulator (SOI) and silicon nitride ($Si_3N_4$–$SiO_2$) — have reached the required degree of maturity to be considered as viable options for the implementation of the complex photonic integrated circuits, either monolithic or hybrid, required by a MWP universal processor.

Figure 1 shows a generic block diagram of the programmable universal integrated MWP processor operating with an arbitrary input radiofrequency signal. This scheme depicts the internal radiofrequency, photonic and control electronic signal flow. The key element of the envisaged chip is the optical core that needs to be reconfigurable and thus programmable.

In a recent paper[6], Leimeng Zhuang and co-workers have proposed a design for a programmable optical core that is inspired by the photonic FPGA-like concept. This approach is based on a 2D waveguide mesh network where the connections between waveguides are controlled by means of tunable Mach–Zehnder interferometers (MZIs). Through external electronic control signals each MZI can be configured to operate as a directional coupler or simply as an optical switch in a cross or bar state providing amplitude- and phase-controlled optical routing, as shown in Fig. 2a. The combination of different MZIs in the 2D grid, each individually configured as desired, enables the synthesis of any kind of circuit topology, including finite and infinite impulse response filters. Figure 2b illustrates a particular implementation of these two general filter configurations. To demonstrate the concept, the researchers fabricated a simplified version of the processor composed of a 2 × 1 mesh network (that is, just two cells) using commercial $Si_3N_4$ waveguide technology known as TriPleX (ref. 4). The reported processor has a free spectral range of

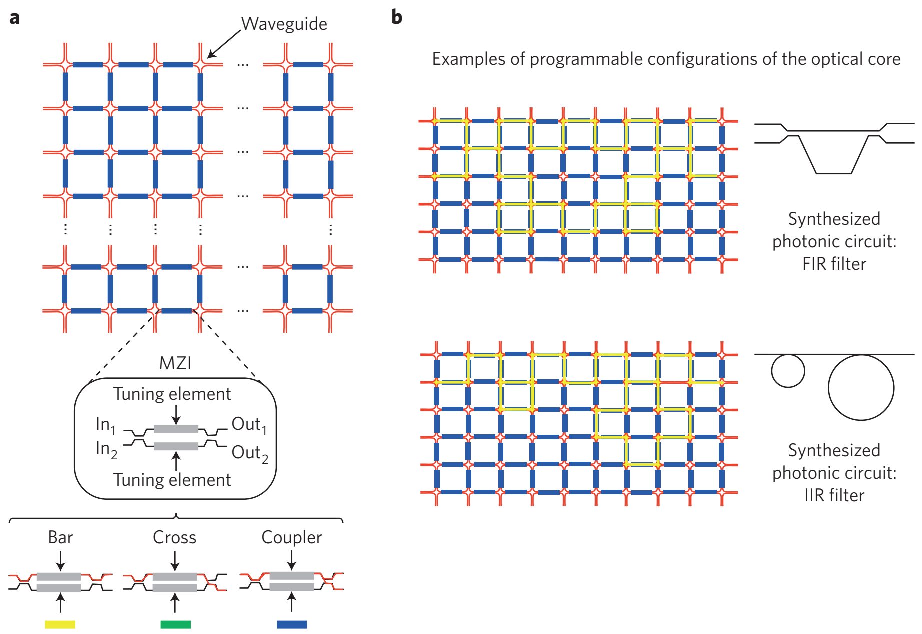


**Figure 2 |** The programmable optical core. **a**, Schematic of a generic 2D mesh network built on interconnected miniature Mach–Zehnder interferometers (MZIs). **b**, Examples of synthesized photonic circuits with a finite impulse response (FIR) and an infinite impulse response (IIR). Figure adapted with permission from ref. 6, OSA.

14 GHz and is fully programmable. By appropriate programming of this processor, Zhuang *et al.* have demonstrated bandpass filters with a tunable centre frequency that spans two octaves (1.6–6 GHz) and a reconfigurable band shape (including flat-top resonance with up to passband–stopband 25 dB extinction). They also report notch filters with up to 55 dB rejection ratio.

The significance of the work is twofold. On one hand, it proposes an original architecture for realizing a universal MWP processor capable of implementing different complex functionalities, using a reconfigurable photonic circuit. On the other, it reports the first, although very simple, experimental demonstration of such a MWP processor. If the concept can be further developed and scaled, its impact in photonic-based radiofrequency processing will be unquestionable. First, MWP systems costs will be greatly reduced as they will benefit from the economies of scale of integrated fabrication, especially if the 2D mesh architecture can be implemented using current state-of-the-art generic integration and generic foundry models[7]. Second, MWP systems oriented to the generation and processing of microwave and millimetre-wave signals will benefit from the compactness of integrated optics technologies. The creation of cost-effective, miniature optical chips capable of performing a myriad of processing tasks would greatly help MWP become attractive for applications such as the Internet of Things, medical imaging systems using terahertz waves, sensor interconnection in wireless broadband personal area networks, wearable communication devices and miniature base stations for femtocell fibre–wireless multiservice radio access networks.

However, to push this concept further towards commercial use there are still some important challenges to be overcome. The first is choosing the right technology platform. While the $Si_3N_4$ platform employed by Zhuang *et al.* features low loss, it is completely passive and this means that optical sources, detectors or amplifiers cannot be monolithically integrated. Hybrid InP–$Si_3N_4$ or InP–SOI approaches[4] can provide a solution.

A second limitation is connected to the required space on the chip to implement a 2D mesh network with a sufficient number of cells. Using $Si_3N_4$, Zhuang *et al.* report a 2 × 1 cell scheme that is fine as a proof-of-concept demonstration but only provides very limited functionality. The MZI length is 3.4 mm while the length of each of the two couplers required in a single cell is 0.675 mm, leading to a cell area of 3.5 × 3.5 $mm^2$.

If we now consider a 10 × 10 cell configuration, the total mesh area will be ~100 times the above-mentioned value. To reduce this footprint it may be necessary to turn to other material platforms that provide a higher refractive index contrast and thus smaller waveguides, such as SOI. Yet, even in this case, a complex 2D mesh will require strict control of waveguide uniformity and roughness along the whole structure to guarantee homogeneous performance.

Another challenge relates to power consumption and heat dissipation. The researchers report that the average power consumption per MZI tuning heater is 0.25 W, which is high for an individual cell if the design is going to be scaled to a much larger number of cells. Furthermore, because tuning in $Si_3N_4$ is based on the thermo-optic effect, it mandates careful control of chip temperature and optimized designs of waveguides and heaters, which may increase the device size. Solutions to this limitation may be achieved by resorting to other platforms featuring electro-optic tuning.

The possibility of developing a universal MWP signal processor is becoming a popular area of research, not only because of the advantages in fabrication costs outlined before, but also because it points to the tantalizing prospect of software-defined MWP. In this sense, the work reported by Zhuang and colleagues is an important development, but it is not the only approach that is being tried and worth exploring.

In particular, Guan and co-workers[8] reported an optical lattice filter based on cascading CMOS-compatible silicon unit cells, each one employing a combination of a ring resonator and a MZI with tunable phase elements in both arms of the inteferometer (see Fig. 2a inset). Also, Wang *et al.*[9] reported a design based on cascading ring resonator stages that demonstrated programmable pulse shaping. Finally, a third alternative involves the design of the optical core using the self-configuring universal linear optical components recently reported by Miller[10]. ❒

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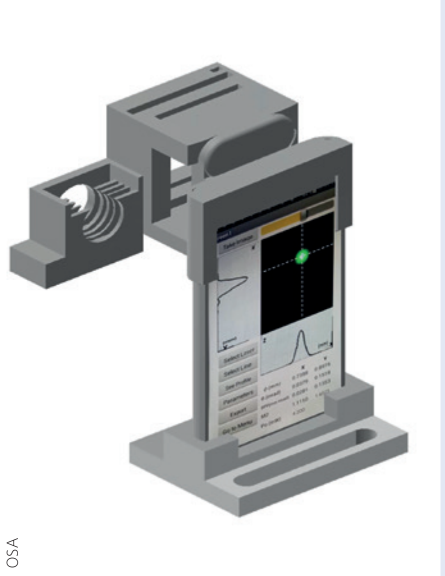
IMAGING AND SENSING

# Portable profiler

Md Arafat Hossain and colleagues from the University of Sydney have developed a smartphone-based ultraviolet laser beam spatial profiler (*Opt. Lett.* **40,** 5156–5159; 2015). Their device, which is low cost thanks to the use of three-dimensional mount printing and the competitive pricing of mobile phone technology, is able to measure a laser beam's spatial profile, output power, divergence and beam quality factor, with all information displayed on the phone's screen and optionally transferred conveniently via the internet.

In their set-up, the ultraviolet beam strikes a 4 cm × 4 cm phosphor glass plate that is normal to the beam's propagation direction. The phosphor plate downconverts the ultraviolet light to visible wavelengths, which is imaged onto the phone's CMOS camera, located 3 cm downstream, via an external lens (thickness, 10 mm; focal length, 10 mm). The phone used is a Kogan 4G, which has an 8 MP rear-facing camera with a maximum signal-to-noise ratio of around 55 dB. Neutral density filters (or other suitable attenuators) are used to avoid saturation of the CMOS sensor. The software to display the beam and its parameters runs on the phone itself. The team evaluated the performance of the scheme by characterizing two ultraviolet lasers: a continuous-wave $Ar^+$ laser (244 nm wavelength) and a pulsed ArF laser (193 nm wavelength, 30 Hz repetition rate, 15 ns pulse duration). Experimental variation in the measurements was comparable to commercial beam profilers.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John Canning, corresponding author for the manuscript, told *Nature Photonics* that the idea worked surprisingly well, and that the main challenge was to ensure measurements could be made both rapidly and reliably. The current system employs a phone running an Android operating system. Canning explained that the Android user-base is several times larger than that of Apple's iOS phones, and that the Android platform may have programming advantages. However, he notes that the same device could be achieved on an iOS system.

"We have already demonstrated combined spectrometer instrumentation with both absorption and fluorescence, so the next direction will be combining multiple instruments onto a single platform," Canning remarked. "For this particular example, adding spectroscopy and linewidth measurements for lasers is potentially feasible. [...] It is also possible to combine laser characterization during spectroscopic analysis so that the beam profile is always understood during excitation of the source being studied."

In their manuscript, the researchers explain that the detection range could be extended to, for example, the near-infrared regime. Canning also noted that the instrument could be made smaller to accommodate other capabilities. There are plans to commercialize some of the team's smartphone instrumentations.

DAVID PILE