Unscrambling light—automatically undoing strong mixing between modes

Andrea Annoni1, Emanuele Guglielmi1, Marco Carminati1, Giorgio Ferrari1, Marco Sampietro1, David AB Miller2, Andrea Melloni1 and Francesco Morichetti1

Propagation of light beams through scattering or multimode systems may lead to the randomization of the spatial coherence of the light. Although information is not lost, its recovery requires a coherent interferometric reconstruction of the original signals, which have been scrambled into the modes of the scattering system. Here we show that we can automatically unscramble optical beams that have been arbitrarily mixed in a multimode waveguide, undoing the scattering and mixing between the spatial modes through a mesh of silicon photonics tuneable beam splitters. Transparent light detectors integrated in a photonic chip are used to directly monitor the evolution of each mode along the mesh, allowing sequential tuning and adaptive individual feedback control of each beam splitter. The entire mesh self-configures automatically through a progressive tuning algorithm and resets itself after significantly perturbing the mixing, without turning off the beams. We demonstrate information recovery by the simultaneous unscrambling, sorting and tracking of four mixed modes, with residual cross-talk of ~20 dB between the beams. Circuit partitioning assisted by transparent detectors enables scalability to meshes with a higher port count and to a higher number of modes without a proportionate increase in the control complexity. The principle of self-configuring and self-resetting in optical systems should be applicable in a wide range of optical applications.

Keywords: optical processing; photonic integrated circuits; silicon photonics; tuneable photonic devices

INTRODUCTION

When a coherent light beam passes through an optical object, interference from scattering or different paths can distort the beam. Strong diffuse scatterers1,2 and even simple multimode fibres or waveguides3,4 can generate complex speckle patterns from simple beams, giving rise to strong scrambling of multiple beams and scrambling any information on these beams5. Historically, for beams of the same wavelength and polarization, an efficient approach for the separation of these beams and channels optically has not been available. This problem is worse if the characteristics of the optical object are not known, and becomes even more severe if the object changes over time.

If the object is measured interferometrically or if some global feedback algorithm is used, the input field required for a desired output field can be calculated1,2,4. A spatial light modulator can set up any one such input field from an input beam, but it cannot simultaneously construct multiple arbitrary overlapping input fields from multiple inputs. In few mode optical fibres or waveguides, specific modes can be separated based on their symmetries and/or different phase velocities6–10, and signals in well-defined modes can be interchanged or switched11,12. However, for arbitrary orthogonal input beams and/or for beams that couple or scatter during the propagation due to imperfections or bends, such approaches cannot generally separate the resulting complex superpositions of output guided modes. Though information can be recovered by coherent detection together with analogue-to-digital conversion and digital electronic multiple input multiple output (MIMO) processing13,14, these approaches require complex digital circuits with associated power, speed and capacity limits.

In waveguides where the loss is essentially the same in all the different propagating modes, in principle, the scattering between the modes can be undone with a unitary linear processor (or, in practice, a processor with uniform loss across all channels). A triangular mesh of 2 × 2 tuneable beam splitters (Figure 1a) is a well-known architecture for the implementation of arbitrary unitary operations15 (see Supplementary Note 1 for discussion of other meshes). While such meshes were successfully implemented in integrated photonics for quantum applications16–18, progressive self-configuring algorithms19–22 were not yet available, leading to the use of time-consuming global calibration and optimization algorithms. Self-configuration of a triangular mesh has been recently demonstrated, though that demonstration was limited to automatic coupling of one input beam and to the rerouting of a single signal through an optical switching matrix23.

1Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano 20133, Italy and 2Ginzton Laboratory, Stanford University, Spilker Building, Stanford, CA 94305, USA
Correspondence: F Morichetti, Email: francesco.morichetti@polimi.it
Received 8 February 2017; revised 23 June 2017; accepted 27 June 2017; accepted article preview online 30 June 2017
Here we demonstrate that strong mixing between modes can be undone all-optically, automatically and without any advance knowledge of the mixing object’s details; furthermore, our approach can adapt to changes in the mixing object in real time. We explicitly demonstrate the separation and reconstruction of four optical beams after these beams were completely and arbitrarily mixed in a multimode waveguide section (mode mixer). Self-conversion is induced on chip through a multimode waveguide section (mode mixer). Self-conversion algorithms are then strongly perturb the guide so that the channels are completely mixed, and demonstrate the automatic recovery of the mode separation.

**MATERIALS AND METHODS**

**Self-configuration of the mesh**

An $N \times N$ triangular array or mesh of $(N-1)/2$ tuneable $2 \times 2$ beam splitters ($S_{m,k}$) is connected according to the mesh and photodetector topology shown in Figure 1a. This mesh enables the factorization of an arbitrary $N \times N$ unitary transformation, described by the transmission matrix $H_{\text{mesh}}$, into a sequence of simple $2 \times 2$ unitary transformations. The evolution of the optical field $E$ along the mesh is given by:

$$E_{m,k+1} = T_{m,k}E_{m,k} = T_{m,k}T_{m,k-1}E_{m,k-1} = \prod_{q=0}^{k-1} T_{m,k-q}E_{m,1}$$

and can be described by the product of $N \times N$ transmission matrices $T_{m,k}$ associated with each beam splitter $S_{m,k}$, where $m = 1, 2, \ldots N-1$ is the progressive index of the mesh reconstructed at the output port of the four guides. Each matrix $T_{m,k}$ can be described by the four-element vector indicating the optical fields contained in the four waveguides of the mesh at the input of stage $(m,k)$, as indicated in Figure 1a. Here we mean a vector in the linear algebra sense, which is technically in a mathematical Hilbert space rather than in a geometrical space. Inside the mesh, a given original input ‘mode’ is represented by such a vector of amplitudes in all four waveguides, and, as such, it could also be referred to as a ‘supermode’ of the four guides. Each matrix $T_{m,k}$ is an $N \times N$ matrix ($4 \times 4$ in Figure 1a) constructed by starting with an identity matrix and then replacing the elements $T_{i,j}$ ($i, j = N-k, N-k+1$) with the elements of the $2 \times 2$ matrix $T_{BS}$ of the tuneable beam splitter.

Figure 1: (a) Schematic concept of an $N \times N$ ($N=4$) triangular mesh of tuneable beam splitters implementing any arbitrary transformation on $N$-dimensional input vectors. Transparent detectors at the output port of each beam splitter monitor the evolution of the optical field $E_{m,k}$ along the entire mesh enabling local control operation on each beam splitter individually. (b) Guided-wave implementation of the mesh through a lattice of two-port cascaded MZIs realizing the tuneable beam splitters controlled through a pair of integrated phase shifters. (c) Silicon photonic four-mode unscrambler consisting of six thermally actuated MZIs individually monitored by transparent CLIPP detectors. Mode scrambling is induced on chip through a multimode waveguide section (mode mixer). Self-configuration and stabilization of the circuit is performed through a CMOS ASIC (d) bridged to the silicon chip, which is connected to an FPGA controller.
where \( \phi_1 \) and \( \phi_2 \) are controllable phase shifts (in Equation (2), subscripts \( m,k \) are omitted for notational simplicity). Each beam splitter \( S_{m,k} \) modifies only the components \( N-k \) and \( N-k+1 \) of the field vector \( E_{m,k} \), leaving the other \( N-2 \) components unchanged. Importantly, at each stage of the mesh, a single transparent light detector (placed on either the waveguide \( N-k \) or \( N-k+1 \)) enables us to follow the (super)mode evolution throughout the entire mesh without impairing the operation of the mesh itself.

To illustrate the self-configuration procedure, consider a first beam shining on the mesh inputs, and hence generating a vector \( E_{11} \) of coherent input beam amplitudes at the input ports. To output all of this beam power at port \( \text{Out}_1 \), the beam splitters \( S_{11}, S_{12} \) and \( S_{13} \) are progressively adjusted to cancel out the power at the embedded detectors\(^{19-21} \). Independent of the relative amplitudes and phases in the input ports, all power from the input vector \( E_{11} \) is automatically combined into one output beam. Mathematically, we can consider this to be a progressive multiplication\(^{20} \) by matrices \( T_{11}, T_{12} \) and \( T_{13} \) that generates vectors \( E_{12}, E_{13} \) and \( E_{14} \), constructing an overall matrix \( M_1 \), and progressively combining these amplitudes into the first element of \( E_{14} \). Since unitary operators preserve orthogonality, if we now shine a second beam with an orthogonal input vector of amplitudes into the mesh, none of that beam appears in port \( \text{Out}_1 \). Hence, all of the second beam will pass through the transparent photodetectors into beam splitters \( S_{21} \) and \( S_{22} \), giving the vector of amplitudes \( E_{21} \) in the lower three guides; those beam splitters can then be similarly automatically aligned to couple all of the second beam to port \( \text{Out}_2 \), implementing an additional matrix \( M_2 \). Configuring each \( m \)-th diagonal row of the mesh, which is associated with the mode reconstruction matrix

\[
M_m = \prod_{k=0}^{N-m-1} T_{m,N-m-k}
\]

we can separate any arbitrary set of four orthogonal input vectors to the four output ports \( \text{Out}_1, \text{Out}_2, \text{Out}_3 \) and \( \text{Out}_4 \) formally implementing an arbitrary unitary transform\(^{20} \). Note that such training does not require any calibration of the phase shifts inside the mesh, and can be completed automatically and progressively in one algorithmic pass through the set of beam splitters.

Here we described turning on the training beams one by one, with the second beam specifically not turned on until the row of beam splitters \( S_{11}, S_{12} \) and \( S_{13} \) is fully configured; similar procedures were conducted for further beams and beam splitter rows. Indeed, such a separated training may always be required when working with simple continuous beams and for related progressive algorithms that can run based on detectors only at the output ports\(^{19,22} \). If, however, the beams of interest are not mutually coherent, and if we can put an identifying ‘key’ on each such training beam, such as a small modulation at a different frequency or ‘tone’ for each beam, then the entire configuration process can be run simultaneously with all beams on at once\(^{19} \).

**Design and technology of the silicon photonic mode unscrambler**

To demonstrate on-chip mode unscrambling, a silicon-photonic 4×4 triangular array of six Mach-Zehnder Interferometers (MZIs) was fabricated on a 220-nm silicon-on-insulator platform through a LETI-ePIXfab multi-project-wafer run (Figure 1b and 1c)\(^{23} \). Tunable beam splitters are realized using thermally actuated balanced MZIs, with 40-μm long directional couplers (300 nm waveguide spacing in the coupling region) and 120-μm long arms spaced by 20 μm. Titanium nitride integrated heaters, with width and length of 1 and 100 μm, respectively, are used to control the phase shifts \( \phi_1 \) and \( \phi_2 \) of the MZIs, providing \( \pi \)-phase shift with an electrical power consumption of \(~10\) mW and a response time of less than 10 μs.

The optical power is locally monitored on chip by transparent CLIPP detectors integrated at the lower output port of each MZI (see Supplementary Note 2 and Supplementary Fig. S1). In the CLIPP detector\(^{24} \), surface-state absorption\(^{25-28} \) in the silicon waveguide gives photoconduction that can be detected capacitively, giving a sub-bandgap all-silicon photodetector for high-sensitivity measurement of light power in the waveguide without introducing any appreciable loss, reflection or phase perturbation in the optical field. The CLIPPs detectors consist of two 20 μm×50 μm electrodes that are mutually spaced by 100 μm and are fabricated using the same metal layer as that used for the heaters and that is placed above the optical waveguides at the distance of \(~600\) nm from the Si core. At a wavelength of 1550 nm, the expected metal loss is on the order of 0.1 dB cm\(^{-1}\); this is more than one order of magnitude below the waveguide propagation loss (1.7 dB cm\(^{-1}\)) and results in a negligible loss of 0.001 dB expected for the CLIPP\(^{24} \). The absence of any relevant absorption implies that the CLIPP monitors the power without introducing any differential absorption in the mesh paths, thus preserving the (super) mode orthogonality. Gold metal strips connect the thermal actuators and the CLIPPs to the 100 μm×100 μm contact pads, where wire-bonding of the photonic chip to the external electronic circuit is performed. Experimentally, we were not able to observe any significant difference between the loss of a waveguide integrating up to 10 CLIPPs with respect to a reference waveguide (with no CLIPPs) with the same length.

Four spatially decoupled input beams (modes A, B, C and D) are injected into the silicon chip through an array of four single mode fibres, which are vertically coupled to the silicon waveguides through a commercial four-channel glass transposer (Figure 1d). The four modes are coupled to the photonic chip through two arrays of input and output grating couplers that are mutually spaced by 127 μm. Mode scrambling is intentionally induced on chip with an integrated mode mixer consisting of a straight multimode waveguide section with four single mode input/output waveguides. The design of the mode mixer was optimized to reduce the loss (see Supplementary Note 3) because loss would impair the orthogonality of the modes, thus affecting the mode reconstruction performed by the MZI mesh. The multimode waveguide is 180-μm long and 10-μm wide, and the single-mode input/output waveguides are linearly tapered up to a width of 2 μm.

This mode mixer can be represented by a matrix \( H \) that maps any vector of each input in modes A, B, C or D in Figure 2a to a resulting vector of field amplitudes at the single-mode waveguide outputs that form the inputs to the mesh. To verify the strong mixing generated by the multimode waveguide, we separately checked an identical standalone mode mixer (fabricated onto the same chip), showing that at a wavelength of 1525 nm, each input mode is scrambled at the output ports with \(~25\%\) power distribution (Supplementary Fig. S2) and with an excess insertion loss lower than 0.7 dB. The integrated mixer provides almost constant mode power coupling across a wavelength range of several tens of nanometres, with negligible differential group delay among the different modes. This situation emulates the mode scrambling that may occur in short links of a few-mode fibre\(^{29} \) (see ‘Results and discussion: On-chip MDM channel unscrambling’ section).
The on-chip attenuation of the MZI mesh (excluding the mode mixer) is less than 1 dB, with ~0.5 dB arising from the silicon waveguide propagation loss and the remaining 0.5 dB due to the excess insertion loss of the directional couplers used in the tuneable beam splitters. To avoid on-chip differential losses as well as to balance all interferometric paths of the mesh, folded waveguide sections are added between the different stages of the mesh. All bends throughout the circuits have a curvature radius of 20 μm, allowing very low reflections and negligible bending losses. The circuit footprint, including metal routing and contact pads, is 3.7 mm × 1.4 mm.

Electronic platform for tuning and locking

For simultaneous read-out of all the CLIPPs integrated in the photonic circuit, a custom-designed multi-channel CMOS ASIC realized in a 0.35-μm AMS CMOS process was bridged to the silicon photonic chip and mounted on the same printed circuit board (Figure 1d)\textsuperscript{30,31}. The ASIC contains a low-noise front-end amplifier followed by a fully integrated lock-in system for the extraction of the in-phase and quadrature components of the light-dependent waveguide impedance\textsuperscript{24}. The ASIC has four parallel read-out channels, with each channel featuring an 8 × input multiplexer to address up to a total of 32 CLIPPs.

When the input modes A, B, C and D are simultaneously coupled into the chip, the CLIPP detectors can identify the power associated with each mode regardless of the presence of other concurrent modes injected at other input ports and scrambled by the mode mixer. To enable mode discrimination, each mode is labelled with a weak ‘key’ or pilot tone before being coupled to the silicon chip. In previous studies, we have demonstrated that such a labelling operation can be performed without affecting the quality of the signals\textsuperscript{32,33}.

Sinusoidal tones with 5% peak-to-peak relative intensity are generated through external MZI lithium niobate modulators biased at the linear working point (3 dB attenuation). The tone frequency $f_q$ is $[4\,\text{kHz}, 7\,\text{kHz}, 10\,\text{kHz}, 11\,\text{kHz}]$ of the $q$-th mode ($q = A, B, C, D$) was suitably chosen to avoid mutual overlap of the overtones that can be generated by the non-perfectly linear response of the modulators. Different tone waves (for example, square waves) as well as different biasing points of the modulator could also be used to reduce the loss associated with tone generation, but such tones would require a more careful selection of the tone frequencies in order to avoid mutual overlaps. To identify the $q$-th mode, the CLIPPs are demodulated twice, first at the read-out frequency $f_{\text{f}}$ around which the CLIPP sensitivity to optical power variations is maximized ($\sim 100\,\text{kHz}$ in the reported experiments, see Supplementary Note 1), and then at the frequency $f_{\text{fi}}$ of the mode to be monitored (see Supplementary Note 4 and Supplementary Fig. S3). Second demodulation at a frequency different from $f_{\text{fi}}$ produces a very low crosstalk signal (lower than $\sim 50\,\text{dB}$), which is mainly due to the noise level of the electronic front-end\textsuperscript{31,33}.

The four output signals from the ASIC are acquired and conditioned by a customized field programmable gate array (FPGA)-based electronic platform and are digitally demodulated at the frequencies $f_{\text{fi}}$ and processed by tuneable infinite impulse response filters (down to 4 Hz bandwidth) to identify the power level of each mode. The FPGA drives the 12 heaters of the silicon photonic chip to tune and lock the 6 MZIs to the desired working points. In the experiments, the system was set to perform the CLIPP read-out in 50 ms, allowing an automatic 2D scan of each MZI ($30 \times 30$ pixel map, as in Figure 2c) in ~45 s and automated full reconfiguration of the mesh (starting from unbiased MZIs) in ~15 s. Once the mesh is configured, tracking of time-varying mixed modes can be performed on a time scale of a few hundred milliseconds. By following the design rules and electronic read-out optimization strategies provided in other specific contributions\textsuperscript{31,34}, the CLIPP read-out time can be reduced by two orders of magnitude, while maintaining a sensitivity better than $\sim 20\,\text{dBm}$, thus enabling the tracking of mode mixing variations occurring within a millisecond range.
Experimental set-up for on-chip unscrambling of MDM channels

A detailed schematic of the experimental set-up employed for the demonstration of on-chip unscrambling of MDM channels is shown in Figure 3. The four channels encoded on modes \{A, B, C, D\} are generated by using a common laser source with an emission wavelength of 1525 nm that is intensity modulated at a data rate of 10 Gbit s\(^{-1}\), according to a 2\(^{11}\)-1 on-off keying pseudo random bit sequence (PRBS) using a commercial LiNbO\(_3\) Mach-Zehnder modulator. After amplification through an erbium-doped fibre amplifier (EDFA), the modulated signal is divided by a 1\(\times\)4 optical fibre splitter. The four data streams are de-correlated using coils of standard single-mode fibres of different lengths, introducing relative delays (>10 ps) that are much greater than the signal coherence length. Variable optical attenuators (VOAs) are employed to equalize the channel optical power to 0 dBm at the input of the silicon photonic circuit. Polarization controllers (PCs) enable the selection of the transverse electric (TE) polarization at the output of the glass transposer (see Figure 1d) in order to optimize the coupling efficiency of each channel with the optical waveguides. At the output ports of the circuit, the transmitted signals are amplified by an EDFA followed by a filter (0.3 nm bandwidth) that is added to reduce the off-band amplified spontaneous emission noise. A VOA is used to control the received power at the input of the photodetector in order to perform the BER and eye diagram measurements.

Light-induced perturbation of the mode mixer

To modify the scrambling process responsible for the mode mixing, the integrated mode mixer was exposed to an intense light beam. To estimate the density of free carriers \(N\) at the input of the photodetector in order to perform the BER measurement, a VOA is used to control the received power at the input of the silicon photonic circuit. The optical power to 0 dBm at the input of the silicon photonic circuit. Polarization controllers (PCs) enable the selection of the transverse electric (TE) polarization at the output of the glass transposer (see Figure 1d) in order to optimize the coupling efficiency of each channel with the optical waveguides. At the output ports of the circuit, the transmitted signals are amplified by an EDFA followed by a filter (0.3 nm bandwidth) that is added to reduce the off-band amplified spontaneous emission noise. A VOA is used to control the received power at the input of the photodetector in order to perform the BER and eye diagram measurements.

\[
\frac{dN}{dt} = \frac{aP}{Ahv} - \frac{N}{\tau}
\]

where \(a\) is the silicon absorption coefficient at 980 nm (\(\approx 100 \text{ cm}^{-1}\)) and \(hv\) is the photon energy (1.26 eV). In silicon waveguides, the free carrier lifetime \(\tau\) typically ranges from a fraction of a nanosecond to several tens of nanoseconds\(^{35}\). Assuming \(\tau = 1\) ns, the steady-state carrier density \(N = \frac{aP}{Ahv}\) is estimated to be on the order of \(2 \times 10^{18} \text{ cm}^{-3}\).

RESULTS AND DISCUSSION

Sorting out mixed modes

To illustrate the reconstruction of modes scrambled by propagation through the mode mixer, in the example of Figure 2a, the first row of the mesh \((M_1)\) is progressively configured to have the optical mode D reconstructed at Out\(_1\). In this experiment, all four input modes, which share the same optical wavelength \(\lambda_0 = 1525\) nm, are switched on, keyed by modulation tones (see Supplementary Note 4 and Supplementary Fig. S3) and injected into the silicon chip with the same power of 0 dBm.

First, MZI \(S_{11}\) (see Figure 2b) is tuned to cancel out the power associated with mode D at the lower output port where CLIPPP is integrated. The map presented in Figure 2c shows the intensity of mode D versus the phases \(\phi_1, \phi_2\) (see Figure 2b) of \(S_{11}\) as measured directly by CLIPPP. The thermal phase shifters are initially set to a non-zero value, such as \(S_{11}(\pi,\pi)\), in order to be able to either increase or decrease the phase shift during the tuning operation. Once convergence to a local minimum \(S_{11}\) is achieved, the procedure is sequentially repeated through the subsequent stages \(S_{12}\) and \(S_{13}\). After the tuning of each beam splitter in the first row of the mesh \((M_1)\), the powers of the sorted mode D and of the concurrent modes A, B and C were measured at port Out\(_1\) over a wavelength range of 20 nm around \(\lambda_0\). As shown in Figure 4, although this mesh configuration process leads to a progressive increase in the output power of the reconstructed mode at Out\(_1\) (Figure 4a1), the crosstalk associated with each concurrent mode does not decrease monotonically as this configuration progresses (Figure 4a1-4a3). For instance, the transmitted power of mode C (Figure 4a1) reaches a minimum after the tuning of \(S_{11}\) and \(S_{12}\); yet the minimization of the overall crosstalk from all the concurrent modes results in an increased transmission of mode C after the tuning of the last stage \(S_{13}\). This indicates that in practice, the mesh configuration cannot necessarily be reliably achieved using only the information provided by external detectors coupled at the output ports, because convergence issues due to local minima can arise, at least if the mesh is not quite perfect. Thus, although an algorithm based only on the overall output powers may work (see the progressive algorithms using only output detectors in Ref. 19 Appendix B and in Ref. 22 and the global algorithms in Ref. 14), approaches with embedded detectors may offer faster and more robust convergence.

Figure 3: Experimental setup used for the demonstration of all-optical unscrambling of mixed MDM channels.
in addition to the ability to configure the mesh when all input modes are present simultaneously.

Any input mode can be reconstructed at any output port with similar performance. For instance, Figure 4b shows that by properly setting $M_1$, mode reconstruction at port Out1 for any particular chosen input is achieved with less than $-20$ dB residual crosstalk of the concurrent modes over a wavelength range of $\sim 10$ nm. More generally, the mesh transmission matrix

$$H_{mesh} = \prod_{m=1}^{N-1} M_{N-m}$$  \hspace{1cm} (5)

can be configured to give any desired permutation of inputs to outputs, as in a switching matrix. In other words, the overall matrix of the system $H_{mesh}H^T$ that describes the power transmission of the input modes $\{A, B, C, D\}$ to the output ports of the mesh, can be chosen to take the form of a generic permutation matrix. This means that not only can the mesh perform an inversion of the $H$ matrix, but the reconstructed modes can also be sorted or switched arbitrarily at the output ports. Figure 5 shows the measured light power at the output ports [Out1, Out2, Out3, Out4] for several configurations of the full mesh. In all considered cases, the power of the concurrent channels is more than $20$ dB below the power of the reconstructed mode (crosstalk data are reported in Supplementary Fig. S4).

Incidentally, we note that this performance is achieved even though the intensity split ratio of the directional couplers of the MZIs is quite far from the ideal 50:50 condition (we estimate $\sim 72\%$ coupling in the fabricated device at $1525$ nm wavelength). Numerical simulations show that an optical crosstalk lower than $-25$ dB is maintained up to a split ratio of $\sim 0.75$, thus implying that no significant performance degradation occurs for relative deviations as large as $50\%$ from the ideal condition (see Supplementary Note 5 and Supplementary Fig. S5). Recent approaches may allow yet further performance optimization even with such imperfect directional couplers$^{22,36}$ and/or with broadband couplers$^{37}$.

On-chip MDM channel unscrambling

To demonstrate the recovery of the information encoded in the optical modes undergoing the mixing process, we injected four data channels (see Figure 6a) that were all at a wavelength of $1525$ nm, on separate fibres to form the inputs A, B, C and D. When the mesh is not configured, mode mixing results in deep time variations in the spectrum of the optical signal measured at the device output (Out1 in Figure 6b) due to the coherent beating of the four spectrally overlapped channels. In contrast, the spectrum of the reconstructed channel exhibits only a tiny frequency-domain ripple due to the residual $-20$ dB crosstalk of the three concurrent channels. The mode mixing leads to the complete closure of the signal eye diagram (insets of Figure 6b), which is effectively restored after mode unscrambling. The panels in Figure 6c show the eye diagrams of each reconstructed channel at port Out1 and do not show any deterioration as more concurrent channels are switched on. Bit error rate (BER) measurements (Figure 6d) show a power penalty $<2$ dB at a BER of $10^{-9}$ as additional channels are turned on.

The MZI mesh can also self-configure automatically to track modes that are mixed by a time-varying scrambling process. The integrated mode mixer was deliberately perturbed by shining a 980-nm-wavelength light beam with an intensity of $3.3$ MW cm$^{-2}$ on it (see Figure 7a). Absorption of this light in the silicon of the mode mixer generates free carriers with a density of $\sim 10^{18}$ cm$^{-3}$, and leads to local changes in the refractive index, arising both from free carrier dispersion (blueshift) and thermal (redshift) effects$^{35}$. These changes affect the self-imaging process along the multimode silicon waveguide$^{38}$ and modify the mode mixer behaviour (Figure 7b). When the 980-nm beam was off (Figure 7b1), the mesh was configured to a reference state where a given channel (A) is reconstructed at one output port (Out1). With the 980-nm beam

![Figure 4](image-url)
on, the mode mixer (Figure 7b₂) is sufficiently perturbed to completely impair mode reconstruction if the mesh is not adaptively configured. Figure 7b₃ shows that the eye diagram of the output channel is successfully recovered after the automatic reconfiguration of the mesh. Notably, this mode reconstruction is performed without any knowledge of the perturbation introduced in the mode mixer.

Transparency to the modulation format is one of the main advantages of performing MDM unscrambling directly in the optical domain. Therefore, we do not expect any significant performance degradation if more advanced modulation formats are employed where both the amplitude and the phase of the signals are modulated. Regarding the optical bandwidth, the realized device provides less than −20 dB residual crosstalk over a bandwidth of ~10 nm, thus posing no significant limitations to the bandwidth of the optical signals that can be manipulated. The tuning strategy itself, which is based on channel labelling with low frequency pilot tones, is inherently independent of the bandwidth and modulation format of the mixed channels, which could indeed have different bandwidths and modulation formats.

Arbitrarily mixed modes can be unscrambled by the proposed mesh, provided that no significant differential mode group delay (DMGD) is accumulated in the mixing channel. This means that the mesh can operate on channels coupled into near degenerate modes (or mode groups) of a multimode fibre propagating with the same group velocity. Because the mesh cannot compensate for an accumulated DMGD, information can be effectively recovered only when the DMGD is a small fraction of the bit time duration (<5%). This situation reflects for instance the case of intradatacentre optical connections, where the length of optical links typically ranges from few tens of metres to a maximum length of 1–2 km. Low values of DMGD have been demonstrated in coupled-core fibres (3.14 ps km⁻¹)⁴⁰ and in cascaded FMFs (<1.7 ps km⁻¹)⁴¹, enabling almost DMGD-free propagation across more than 2 km at 10 Gsym s⁻¹, or 500 m at 40 Gsym s⁻¹.

CONCLUSION

We have demonstrated all-optical mode reconstruction, unscrambling and sorting in a silicon photonic circuit using a self-reconfiguring interferometric mesh. Because each mesh element (tuneable beam splitter) is locally monitored and feedback-controlled by transparent detectors, the progressive self-configuration of the mesh is reduced to a repeated two-degrees-of-freedom problem independently of the
modes. (silicon chip in order to modify the relative amplitude and phase of the mixed light source (980 nm) is used to perturb the mode mixer integrated in the manipulation of a large number of modes20.

For implementation on existing silicon photonics platforms, the practical limit to the mesh scalability is neither the physical size of the mesh, nor the complexity of the tuning and locking algorithm, because meshes with more than one thousands tuneable splitters and handlers several tens of modes could be realized and controlled. Power consumption of thermal actuators and propagation loss of the silicon waveguide is the main barrier to scalability to a very large number of modes (see the Supplementary Information for a quantitative analysis). This overall concept of transparent on-chip monitoring and adaptive feedback control of elementary photonic elements can be extended to arbitrary mesh topologies, such as the topologies that have been recently proposed to implement programmable photonic processors18,42–45.

Mode unscrambling on a photonic chip can also be exploited to improve the performance of recently proposed silicon photonics devices for the manipulation of MDM optical channels6–11, where a one-by-one mapping of the modes of single-mode waveguides to predetermined modes of multimode waveguides is performed. In these examples, no mode coupling in the multimode waveguide is considered, but in reality, mode mixing could be induced by sharp bending, waveguide crossing, as well as fabrication imperfections. Mode unscramblers, such as the one proposed in this work, can be extended to arbitrary mesh topologies, such as the topologies that have been recently proposed to implement programmable photonic processors18,42–45.

Figure 6 On-chip unscrambling of MDM optical channels. (a) Information encoded in four scrambled 10 Gbit s–1 intensity modulated MDM channels is recovered after mode reconstruction performed by the silicon photonic mesh. (b) As a consequence of mode mixing, the spectrum of the four mixed channels (black curves) exhibits deep time-varying oscillations, which disappear after successive measurements taken at output port Out1. The corresponding time domain signals are shown in the eye diagrams in the insets. Eye diagram (a) and BER (d) measurements (port Out1) demonstrate that information encoded in each channel can be retrieved with a very small power penalty independent of the number of mixed modes.

Figure 7 Reconstruction of modes scrambled by time-varying mixing. (a) A light source (980 nm) is used to perturb the mode mixer integrated in the silicon chip in order to modify the relative amplitude and phase of the mixed modes. (b) After configuring the mesh to reconstruct channel A at port Out1, the 980-nm source is switched on to modify the mode mixing, thus impairing mode reconstruction at the mesh output (perturbed state, b2). In the track mode b3, the mesh adaptively self-configures by controlling each MZI through a local feedback loop, in order to automatically compensate against time-varying mixing of the modes.

For implementation on existing silicon photonics platforms, the practical limit to the mesh scalability is neither the physical size of the mesh, nor the complexity of the tuning and locking algorithm, because meshes with more than one thousands tuneable splitters and handling several tens of modes could be realized and controlled. Power consumption of thermal actuators and propagation loss of the silicon waveguide is the main barrier to scalability to a very large number of modes (see the Supplementary Information for a quantitative analysis). This overall concept of transparent on-chip monitoring and adaptive feedback control of elementary photonic elements can be extended to arbitrary mesh topologies, such as the topologies that have been recently proposed to implement programmable photonic processors18,42–45.

Mode unscrambling on a photonic chip can also be exploited to improve the performance of recently proposed silicon photonics devices for the manipulation of MDM optical channels6–11, where a one-by-one mapping of the modes of single-mode waveguides to predetermined modes of multimode waveguides is performed. In these examples, no mode coupling in the multimode waveguide is considered, but in reality, mode mixing could be induced by sharp bending, waveguide crossing, as well as fabrication imperfections. Mode unscramblers, such as the one proposed in this work, are thus required to mitigate these effects, which are difficult to predict at design time, and which potentially also vary in time in uncooled photonic chips because of the different temperature sensitivities of the different guided modes.

While our demonstration architecture is capable of implementing any unitary (that is, loss-less) linear function between inputs and outputs, architectural extensions allow this approach to implement non-unitary linear operations also. In applications where mode mixing must be tracked with a control system that neither reaches the end of
its range (endless) nor needs to reset (resetless) to avoid communication interruptions, endless phase shifters could be integrated in the tunable beam splitters of the mesh, though necessarily at the cost of an increasing complexity of the photonic circuit. Likewise, more complex meshes would be required to unscramble optical modes that have experienced mode-dependent loss and large DMGD. For instance, it has been shown that two unitary processors as described here can be used to undo the scattering between the modes even when the losses in the modes differ substantially from each other. The approach presented here can also be extended to other semiconductor photonics platforms, such as InP, where modes are not easily separable because of the similarity of their phase velocities and where the CLIPPP operation has also been successfully demonstrated. We expect that this approach will find use in mode (de)multiplexers, multimode switches, mode converters, switchable mode exchangers and other programmable photonic processors for applications in a variety of different fields, such as telecommunications, imaging, sensing, secrecy, and quantum information processing.

**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

**AUTHOR CONTRIBUTIONS**

FM conceived the experiments and supervised the work. AA designed the photonic chip and performed the experiments. EG developed the firmware and performed the experiments; MC designed and tested the electronic platform; GF designed the CMOS ASIC; MS supervised the implementation of the electronic platform; AA, FM and AM analysed the data; FM, AM and DM wrote the manuscript.

**ACKNOWLEDGEMENTS**

The research leading to these results received funding from the European Union’s Seventh FP7 Programme (Grant agreement No. 323734, BBOI), from the European Union’s H2020 Programme (Grant No. 688172, STREAMS), from Fondazione Cariplo (Grant No. 2016-0881, ACTIO) and by Multi- disciplinary University Research Initiative grant (Air Force Of Science and Technology, FA9550-12-1-0024). This work was (partially) performed at Polifab, the micro- and nanofabrication facility of Politecnico di Milano (www.polifab.polimi.it). The authors acknowledge F Zanetto for assistance with measurements.

1 Vellekoop IM, Most AP. Focusing coherent light through opaque strongly scattering media. Opt Lett 2007; 32: 2309–2311.
2 Mosk AP, Lagendijk A, Lenosky G, Fink M. Controlling waves in space and time for imaging and focusing in complex media. Nat Photonics 2012; 6: 283–292.
3 Ryf R, Fontaine NK. Space-division multiplexing and MIMO processing. In: Zhou X, Xie CJ editors. Enabling Technologies for High Spectral-Efficiency Coherent Optical Communication Networks. John Wiley & Sons, Inc. 2016; pp 547–568.
4 Pöschner M, Tyc T, Arik SÖ, Kahn JM. Direct-detection mode-division multiplexing in modal basis using phase retrieval. Opt Lett 2016; 41: 4265–4268.
5 Reck M, Zeilinger A, Bernstein HJ, Bertani P. Experimental realization of any discrete unitary operator. Phys Rev Lett 1996; 75: 616–618.
6 Lackmann R, Rau T, Aravind LB, Bogaerts W. Demonstration of a 4×4-port universal linear circuit. Optica 2016; 3: 1348–1357.
7 Crespi A, Osellame R, Ramponi R, Brod DJ, Gállová EF et al. Integrated multimode interferometers with arbitrary designs for photonic boson sampling. Nat Photonics 2013; 7: 545–549.
8 Harris NC, Steinbrecher GR, Prabhuj M, Lahini Y, Mower J et al. Quantum transport simulations in a programmable nanophotonic processor. Nat Photonics 2017; 11: 447–452.
9 Miller DAB. Self-aligning universal beam coupler. Opt Express 2013; 21: 6360–6370.
10 Miller DAB. Self-configuring universal linear optical component. Photonics Res 2013; 1: 1–15.
11 Miller DAB. Reconfigurable add-drop multiplexer for spatial modes. Opt Express 2013; 21: 20220–20229.
12 Miller DAB. Perfect optics with imperfect components. Optica 2015; 2: 747–750.
13 Ribeiro A, Ruscio A, Vanacker L, Bogaerts W. Demonstration of a 4×4-port universal linear circuit. Optica 2016; 3: 1348–1357.
14 Morichetti F, Grillasca S, Carminati M, Ferrari G, Sampietro M et al. Non-invasive on-chip light observation by contactless waveguide conductivity monitoring. IEEE J Sel Top Quantum Electron 2014; 20: 292–301.
15 Morichetti F, Annoni A, Grillasca S, Feserino N, Carminati M et al. Channel-All-Optical MIMO Demultiplexing on a Silicon Chip. Proceedings of Optical Fiber Communication Conference, 20-22 March 2016; Anaheim, California United States. Optical Society of America: Anaheim, California, USA 2016.
16 Baehr-Jones T, Hochberg M, Scherer A. Photodetection in silicon beyond the band edge with surface states. Opt Express 2008; 16: 1659–1668.
17 Chen H, Luo XS, Poon AW. Cavity-enhanced photocurrent generation by 1.95 μm wavelengths linear absorption in a p-i-n diode embedded silicon microring resonator. Appl Phys Lett 2009; 95: 171111.
18 Grillasca S, Morichetti F. Light-induced metal-like surface of silicon photonic waveguides. Nat Commun 2015; 6: 6182.
19 Photodetector RC, Doer CR, Mestres MA, Ryf R, Winzer P et al. Space-Division Multiplexing and All-Optical MIMO Demultiplexing Using a Photonic Integrated Circuit. Proceedings of National Fiber Optic Engineers Conference; 4-8 March 2012; Los Angeles, California, USA. Optical Society of America: Los Angeles, California, USA 2012.
20 Grillasca S, Carminati M, Morichetti F, Ciccarella P, Annoni A et al. Non-invasive monitoring and control in silicon photonics using CMOS integrated electronics. Optica 2014; 1: 129–136.
21 Ciccarella P, Carminati M, Ferrari G, Bianchi D, Grillasca S et al. Impedance-sensing CMOS chip for noninvasive light detection in integrated photonic circuits. IEEE Trans Circuits Syst I II 2016; 63: 929–933.
22 Grillasca S, Morichetti F, Pescero N, Ciccarella P, Annoni A et al. Non-invasive monitoring of mode-division multiplexed channels on a silicon photonic chip. J Lightwave Technol 2015; 33: 1197–1201.
23 Annoni A, Guglielmi E, Carminati M, Grillasca S, Ciccarella P et al. Automated routing and control of silicon photonic switch fabrics. IEEE J Sel Top Quantum Electron 2016; 22: 3600408.
24 Carminati M, Annoni A, Morichetti F, Guglielmi E, Ferrari G et al. Design guidelines for contactless integrated photonic probes in dense photonic circuits. J Lightwave Technol 2017; 35: 3042–3049.
25 Lin Q, Painter OJ, Agrawal GP. Nonlinear optical phenomena in silicon waveguides: Modeling and applications. Opt Express 2007; 15: 16604–16644.
26 Wilkes CM, Jiang W, Yang J, Santagati R, Paesani S et al. 60 GHz high-extinction auto-configured Mach-Zehnder interferometer. Opt Lett 2016; 41: 5318–5321.
27 Hail R, Cheben P, Luque-Gonzalez JM, Sarriente-Meregale JD et al. Ultra-broadband nanophotonic beam splitter using an anisotropic sub-wavelength metamaterial. Laser Photonics Rev 2016; 10: 1039–1046.
28 Bruck R, Vync K, Latorre P, Mills B, Thomson DJ et al. All-optical spatial light modulator for reconfigurable silicon photonic circuits. Optica 2016; 3: 396–402.
29 Zhou X, Liu H, Urita R. Datacenter optics: requirements, technologies, and trends. Chin Opt Lett 2017; 15: 120008.
30 Hayashi T, Tamura Y, Hasegawa T, Taru T. Record-low spatial mode dispersion and ultra-low loss coupled multi-core fiber for ultra-long-haul transmission. J Lightwave Technol 2017; 35: 450–457.
31 Randel S, Ryf R, Gnauck A, Mestres MA, Schmidt C et al. Mode-Multiplexed 6×20-Gb/s Transmission over 1200-km DGD-Compensated Few-Mode Fiber. Proceedings of National Fiber Optic Engineers Conference; 8-12 March 2012; Los Angeles, California, USA. Optical Society of America: Los Angeles, California, USA 2012.
32 Clemens WR, Humphreys PC, Metcalf BJ, Kolthammer WS, Walmsley IA. Optical design for universal multiport-interferometers. Optica 2016; 3: 1460–1465.
33 Shen YD, Harris NC, Skirlo S, Prabhuj M, Baehr-Jones T et al. Deep learning with coherent nanophotonic circuits. Nat Photonics 2017; 11: 441–446.
Supplementary Information for this article can be found on the *Light: Science & Applications* website (http://www.nature.com/lsa).
Supplementary Information for
“Unscrambling light – automatically undoing strong mixing between modes”

Andrea Annoni\textsuperscript{1}, Emanuele Guglielmi\textsuperscript{1}, Marco Carminati\textsuperscript{1}, Giorgio Ferrari\textsuperscript{1}, Marco Sampietro\textsuperscript{1}, David A. B. Miller\textsuperscript{2}, Andrea Melloni\textsuperscript{1}, Francesco Morichetti\textsuperscript{1}

\textsuperscript{1}Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133 Milano, Italy
\textsuperscript{2}Ginzton Laboratory, Stanford University, Spilker Building, 348 Via Pueblo Mall, Stanford CA 94305, USA

Correspondence: F. Morichetti, Email: francesco.morichetti@polimi.it
Supplementary note 1: Photonic mesh architectures implementing arbitrary linear operations

At present, three architectures, made up from meshes of 2×2 interferometers, are known that can implement arbitrary unitary transforms between a vector of optical input amplitudes and a corresponding vector of output amplitudes for coherent light at a given wavelength: a “triangular mesh” architecture¹⁻⁵ (which is used in our work here), a “cascaded binary tree” architecture³, and a “rectangular mesh” architecture⁶. Of these, both “triangular mesh” and “cascaded binary tree” architectures can be configured automatically using “training” vectors of inputs and simple progressive algorithms based on detection and simple one- or two-parameter feedback minimization processes³,⁴. In these “trainable” architectures, a given linear transform is trained using vectors that are the Hermitian adjoints of the desired rows of the corresponding matrix (as we do in this work). All three of these architectures require only a number of phase shifters that corresponds to the number of real numbers required to specify an arbitrary N×N unitary matrix, and so are optimally efficient in that sense.

For non-unitary transforms (i.e., arbitrary matrices), two architectures are known: an architecture based on the singular value decomposition (SVD) of the desired matrix⁴, and one based on the use of a 2N×2N unitary matrix to implement an N×N non-unitary transform by operator dilation². The SVD approach can be “trainable” and has the minimum number of required phase shifters. The SVD approach can be implemented using two unitary transforms and an additional row of modulators⁴. Each such unitary transform can be implemented using any of the above unitary architectures. If “trainable” unitary transform meshes are used, the overall non-unitary function can be trained using appropriate vectors at the inputs for one of the unitary transforms, and by shining appropriate vectors back into the output for training the other unitary transform. Hence the self-configuring approach of our work could also be applied to implement “trainable” non-unitary transformations that mathematically could also undo scattering with different loss on different modes.

Supplementary note 2: Electronic read-out of the CLIPP monitor

The working principle of the CLIPP monitor is extensively discussed in Ref. [7], where the CLIPP concept was demonstrated for the first time. For completeness’ sake, in this section, we briefly recall the main features related to the CLIPP operation and electronic read-out.

The CLIPP monitors the light intensity in the waveguide by measuring the light-dependent variation of the conductance ΔG of the waveguide. Non-invasive monitoring is achieved by remotely performing an impedance measurement without electrically contacting the CLIPP electrodes with the Si core. A top-view picture of one of the CLIPPs integrated in the MZI mesh used in this work is shown in Supplementary Figure S1a. To by-pass the access capacitance provided by the insulating SiO₂ top cladding, the CLIPP electrodes are AC-coupled to the Si waveguide core. The CLIPP readout requires a low-noise transimpedance amplifier (TIA) and a lock-in detection scheme that are both integrated into the CMOS ASIC connected to the silicon chip. Details on the design of the ASIC can be found in Ref. [8], where a complete block diagram of the electronic circuit is provided.
A sinusoidal voltage $V_e$ at frequency $f_e$ is applied to one of the CLIPP electrodes, while the current $i_e$ at the other electrode is collected with a synchronous electrical detection architecture. Since the CLIPP is partly made by the silicon waveguide core (resistor) and partly made by the electrode-cladding interface (capacitor), the current $i_e$ is in general out of phase with respect to the applied voltage $V_e$. In order to measure the conductance of the silicon waveguide, whose variation provides information on the light intensity in the waveguide, the in-phase component (real part of the complex impedance) has to be extracted. This is done externally in the FPGA by processing the acquired in-phase and quadrature components of the overall waveguide impedance.

Supplementary Figure S1b shows the electrical signal (conductance variation $\Delta G$) provided by a stand-alone test CLIPP fabricated on the same chip of the MZI mesh as a function of the readout frequency $f_e$ for increasing optical power level. Maximum sensitivity to optical power variation is observed around 100 kHz. At this frequency, the responsivity curve of the CLIPP (Supplementary Figure S2c) shows a sensitivity of at least -20 dBm with a dynamic range of 30 dB. This sensitivity enables accurate monitoring of each MZI tuneable beam splitter to achieve mode reconstruction with a -20 dB residual crosstalk.

**Figure S1.** Performance assessment of the CLIPP monitor. (a) Top view photograph of the one of the CLIPPs integrated in the MZI mesh and block diagram of the electronic circuit integrated in the CMOS ASIC for the read–out of the CLIPP; (b) Electric signal provided by the CLIPP versus the frequency of the applied voltage signal for increasing optical power in the silicon waveguide. (c) Responsivity curve of the CLIPP measured at a frequency $f_e = 100$ kHz, where the sensitivity to light variation is maximum.
**Supplementary note 3: Integrated mode mixer**

The integrated mode mixer responsible for mode scrambling consists of a multi-mode waveguide section with four input ($I_1, \ldots, I_4$) and four output ($O_1, \ldots, O_4$) single mode waveguides, resulting in the multimode interference coupler shown in the schematic of Supplementary Figure S2a. Electromagnetic simulations based on the Eigenvalue Mode Expansion (EME) method were performed to optimize the design of the mode mixer in order to reduce the loss created by the imperfect self-imaging of the field at the output port of the multimode region (see Supplementary Figure S2b). To reduce the loss, the 480-nm wide single-mode input/output waveguides are linearly tapered up to a width of 2 μm. In the circuit presented in this work, the mode mixer integrated before the MZI mesh is 180 μm long and 10 μm wide. Supplementary Figure S2c shows the spectral response of a stand-alone mode mixer that was fabricated on the same chip for testing purposes. When the light is injected from one input port (due to the symmetry of the device, only curves referring to inputs $I_1$ and $I_2$ are shown) an almost-wavelength-independent 25% (± 2%) mode splitting is observed at all four output ports, thus maximizing the mode scrambling between the input modes. The overall insertion loss of the mode mixer was evaluated by comparing the sum of the power leaving the output ports to the power collected from a reference straight waveguide; for every input port an excess insertion loss lower than 0.7 dB was estimated, thus confirming that mode scrambling is performed without impairing mode orthogonality.

**Figure S2.** Optical characterization of the integrated mode mixer. (a) Schematic and (b) electromagnetic simulation of the mode mixer. (c) The fabricated mode mixer splits the input power of each input mode to all four output ports with a 25% (± 2%) split ratio over the 1520 - 1540 nm wavelength range considered in this work.
Supplementary note 4: Mode labelling and identification with modulation tones

The effectiveness of the mode identification performed by the CLIPP and its use for the monitoring of the tuneable beam splitters of the mesh is shown in Supplementary Figure S3. The three maps show the signal provided by CLIPP1 when the beam splitter $S_{11}$ is tuned by changing the phases $\phi_1$ and $\phi_2$. With respect to the case where only one mode (D) is injected in the mesh (a), the presence of concurrent channels strongly modifies the map [in (b) also channel B is switched on], hindering the biasing of the MZI at the proper working point for mode D reconstruction. Mode labelling through pilot tones (c) enables monitoring and control of the state of the MZI with no side effects associated with the presence of the concurrent channels.

**Figure S3.** CLIPP-assisted monitoring of the tuneable beam splitters of the mesh by using mode labelling. Maps show the signal measured by CLIPP1 during the tuning operation of the beam splitter $S_{11}$ as a function of $\phi_1$ and $\phi_2$, when: (a) only mode D is injected in the mesh, concurrent modes are off and no tone is applied; (b) concurrent mode B is switched on, no tone is applied and the CLIPP is read at frequency $f_o$; (c) concurrent mode B is switched on, a tone at frequency $f_D$ is applied on mode D and the CLIPP is read at frequency $f_o + f_D$. 
Figure S4. Logarithm scale representation and measured crosstalk data of the permuted mode reconstructions reported in Figure 5.
Supplementary note 5: Tolerance analysis of mode reconstruction

Numerical simulations were performed by using the transmission matrix method (TMM) to investigate the sensitivity of the mesh to fabrication imperfection in the directional couplers of the MZIs. Supplementary Figure S5 shows the overall crosstalk, averaged over a bandwidth of 10 nm around 1525 nm, that is provided by the other three concurrent channels when channel A (solid blue), B (dashed red), C (dashed-dotted green), and D (dotted yellow) are respectively reconstructed at the output port Out1. Results are reported only for split ratios > 0.5 because crosstalk curves are symmetrical with respect to the ideal condition (3 dB directional coupler). A crosstalk lower than -25 dB is observed up to a split ratio as high as 0.75 (or equivalently 0.25 for the under-coupled case), thus implying that no significant crosstalk degradation occurs for relative deviations as large as 50% from the ideal condition.

Figure S5. Robustness of mode reconstruction versus fabrication tolerances in the directional coupler of the mesh. Curves show the simulated crosstalk given by the all the concurrent channels when mode A (solid blue), B (dashed red), C (dashed-dotted green), and D (dashed yellow) is reconstructed at the port Out1. No significant crosstalk degradation is observed up to a 50% split ratio deviation from the ideal 0.5 condition.
Supplementary note 6: Practical limits to the scalability of the mesh

In this section, we provide some information on the practical limits to the scalability of the mesh for implementation on existing silicon photonics platforms. Given the number $N$ of modes to be unscrambled, the number of required tunable switches (Mach-Zehnder interferometers) of the mesh scales up as $N(N-1)/2$. To give an example, unscrambling of 64 modes will require 2016 Mach-Zehnder interferometers.

In the following, we address several issues to point out where practical limits to the realization of a mesh with such a size could arise from:

Physical size of the mesh. Considering the mesh density of the fabricated device ($0.25 \text{ mm}^2$ footprint for each Mach-Zehnder interferometer, including CLIPP monitors), the footprint of a 64 mode unscrambler would be about 5 cm$^2$. This size is still compatible with silicon photonics chips. However, we should consider that the mesh density of the fabricated device is not constrained by the photonic layer, but by the metal lines connecting CLIPPs and heaters to the bonding pads. The footprint of the mesh could be significantly reduced by using flip-chip technology, where the CMOS ASIC is directly bonded on top of the photonic chip, thus removing the need for most electrical wiring across the chip.

Optical loss. In the considered mesh topology, no waveguide crossings are required, so that insertion losses depend only on waveguide propagation loss and excess insertion loss in the directional couplers of the Mach-Zehnder interferometers. The maximum number of Mach-Zehnder interferometers of the mesh that are passed through by each mode increases linearly with the number of modes $N$. In the realized 4 mode mesh a loss of about 1 dB loss is observed; the loss increases to about 16 dB for a 64 mode unscrambler realized with the same silicon photonics technology.

Electrical power dissipation. The thermal actuators employed in this work require about 10 mW for a $\pi$ shift, resulting in a maximum power consumption of 120 mW for the configuration of the full mesh (integrating 12 heaters). A 64 mode unscrambler with 2016 Mach-Zehnder interferometers (4032 heaters) would thus require an unpractically high dissipation of about 40 W. Therefore, alternative phase actuators or low-power consumption heaters are required to enable scalability of the mesh to a large number of modes.

Tuning and control. One of the main benefits of the proposed progressive self-configuring algorithms is that it can work independently of the mesh size. However, since the mesh is configured through a step-by-step algorithm, the time required for the full configuration of the mesh scales up linearly with the number of mesh elements (that is quadratically with the number of mixed modes $N$). This issue could be overcome by using more advanced tuning algorithms. For instance, one can think to parallelize the tuning of some mesh elements that are not interferometrically connected, such as tunable splitters $S_{13}$ and $S_{21}$ of the mesh employed in this work. In addition, CLIPP detectors would enable partitioning of the mesh in small clusters of Mach-Zehnder interferometers, which could be locally monitored and simultaneously tuned by using multi-degree-of-freedom algorithms.

Therefore, for implementation on existing silicon photonic platforms, power consumption of thermal actuators and propagation loss of the silicon waveguide represent today the main barrier to the scalability of the mesh to a large number of modes.
References

1 Reck M, Zeilinger A, Bernstein HJ, Bertani P. Experimental realization of any discrete unitary operator. Phys Rev Let 1994; 73: 58-61.
2 Carolan J, Harrold C, Sparrow C, Martín-López E, Russell NJ et al. Universal linear optics. Science 2015; 349: 711-716.
3 Miller DAB. Self-aligning universal beam coupler. Opt Express 2013; 21: 6360-6370.
4 Miller DAB. Self-configuring universal linear optical component. Photonics Res 2013; 1: 1-15.
5 Ribeiro A, Ruocco A, Vanacker L, Bogaerts W. Demonstration of a 4 × 4-port universal linear circuit. Optica 2016; 3: 1348-1357.
6 Clements WR, Humphreys PC, Metcalf BJ, Kolthammer WS, Walmsley IA. Optimal design for universal multiport interferometers. Optica 2016; 3: 1460-1465.
7 Morichetti F, Grillanda S, Carminati M, Ferrari G, Sampietro M et al. Non-invasive on-chip light observation by contactless waveguide conductivity monitoring. IEEE J Sel Top Quantum Electron 2014; 20: 292-301.
8 Ciccarella P, Carminati M, Ferrari G, Bianchi D, Grillanda S et al. Impedance-sensing CMOS chip for noninvasive light detection in integrated photonics. IEEE Trans Circuit Syst II: Express Briefs 2016; 63: 929-933.