Reconfigurable linear optical networks are a key component for the development of optical quantum information processing platforms in the NISQ era and beyond. We report the implementation of such a device based on an innovative design that uses the mode mixing of a multimode fiber in combination with the programmable wavefront shaping of a SLM. The capabilities of the platform are explored in the classical regime. For up to 8 inputs and a record number of 38 outputs, we achieve fidelities in excess of 93%, and losses below 6.5 dB. The device was built inside a standard server rack to allow for real world use and shows consistent performance for 2x8 circuits over a period of 10 days without re-calibration.

I. LINEAR OPTICAL QUANTUM COMPUTING

Photons are excellent carriers of quantum information: They are resistant to decoherence and can easily propagate over large distances. Mature technologies for controlling their creation, propagation, and detection are now available, or on the cusp of becoming useful. They also allow to interface between other quantum platforms like ions [1], neutral atoms [2], spin [3] and superconducting qubits [4]. Taken together, these properties give them a unique standing in the development of applications in the NISQ era and beyond.

A recent implementation of optical quantum information processing (QIP) [5] demonstrated supremacy over classical computers for the first time, but only for one specific and fixed task [6]. One of the most promising avenues for practical and scalable optical QIP are programmable linear optical networks [7–10]. They are needed to implement QIP both in circuit model [10] and cluster state approaches [11–12], and could find applications in diverse fields such as quantum transport [13–16], quantum repeaters [17], and quantum machine learning [18–21]. Photonic integrated circuits are a popular choice for the implementation of such systems [22–26]. Here the linear circuit is implemented via the propagation of light through a series of beam splitters and phase shifters in an integrated waveguide architecture. These systems see steady improvement, but their scalability is currently hindered by fabrication complexity, thermal stability and electrical control.

3D wave mixing in complex media in conjunction with wavefront shaping is a promising alternative approach. The implementation of a simple beam splitter [27–30] as well as more complex linear circuits [31–32] have been demonstrated. As any n-input, m-output circuit can be implemented in principle as long as the number of controlled modes is greater than n * m [33], and because waveguides with propagation modes numbering well beyond the tens of thousands are readily available, the platform shows great potential for scalability. Furthermore, there is the possibility to interface with a wider range of optical systems of various wavelengths including outside the NIR/telecom range. Demonstrations so far have been proofs of concepts in a laboratory environment. To enable their use in the ever-expanding context of NISQ, QIP necessitates more integrated and transportable designs. Furthermore, while this approach has been tested for circuits with up to 2 input ports, many applications require a larger circuit, in particular when working with dual-rail encoding [21].

In this paper, we report on the realization of a multimode-fiber-based optical linear processor installed in a standard server rack. After a classical characterization it is shown to allow for arbitrary linear quantum circuits with size up to 8x38, fidelities above 93% and losses below 6.5 dB. We describe the so-called QORE processor and its working principle before providing a study of its performance in the classical regime in terms of circuit fidelity, stability and coupling.

II. QORE: PRINCIPLE

The operating principle of the device is shown in Fig. 1(a). The process harnesses the polarization and spatial mode-mixing properties of a multimode fiber (MMF) in conjunction with the wavefront shaping capabilities of a spatial light modulator (SLM) to implement the desired optical circuit L. The wavefronts of incoming input fields on the left of the figure are shaped through the application of suitable phase masks on the SLM before being coupled into the MMF. The output fields are then verified to follow L, both in the classical regime or using single photon detectors.

Each incoming input field is mapped onto the appropriate modes of the MMF in two steps. First the measurement of the MMF’s transfer matrix (TM) is performed following a phase-stepping holographic method. In this method, the fiber input mode basis is probed by displaying on the SLM gratings of various directions and periods added to a global dephasing, and the resulting output fields are recorded with the chosen detection system (see

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The concept has been presented and used in \cite{31, 32} in the context of up to two optical inputs distinct in polarization. Here we report the extension of the system to 8 inputs as well as its characterization. Each input is incident on the SLM (Holoeye Pluto-2-NIR-080) as a gaussian beam before the appropriate phase masks are applied. The SLM is in the Fourier plane relative to the input facet of the MMF. Figure 2(b) shows the input beams in that plane in red. The MMF aperture (shown as a black circle) limits the acceptable range of input modes. One can see that the available area for each input decreases as their number grows. Consequently the number of MMF modes per input decreases, leading to a change in performance that we characterize in section III. As an illustration, Fig. 1(a) shows the configuration corresponding to 2 input railings per polarization. We tested the system for configurations going up to 8 inputs.

Along with the input basis, the realization of optical circuits requires the definition of an output basis, or railings. Ultimately, these output railings aim to be matched to detection or propagation channels. In our case the quality of circuits is tested using two kinds of detection systems: a CMOS camera (Basler aca2000) and an array of 23 avalanche photodiodes (Pi Imaging SPAD23). Both are imaging the output facet of the MMF. The rotation of the half-waveplate at the output allows us to monitor both polarizations either with the camera or the single-photon detector array. With the camera, the output modes are defined as a set of zones on the sensor with an area on the order of the speckle grain size. In the case of the SPAD23, a total of 46 output modes are defined as the active areas of the 23 detectors, monitored on both polarizations. With these definitions set, one can see that we are able to evaluate the performance of the system in a variety of input-output number configurations \( n \times m \) using a single input beam: To adapt to the input configuration \( n \), we simply suitably offset and resize the beam on the SLM plane following the dashed-red circles in Fig. 1(b). We can then monitor \( m \) detection modes to match the output setting.

### III. QORE: Capability

In Figures 2(a) and 2(b), we present experimentally implemented circuits as measured using the SPAD23 in the configuration corresponding to 2 inputs and variable output number settings. Fig 2(b) in particular illustrates the control we have on the circuit generation in the case of 38 outputs. As shown on top, we used here as a target circuit a non-unitary matrix reproducing the LightOn logo. Each line of the matrix was implemented in sequence and then measured to obtain the data-set displayed on the bottom. From this information, the quality of the implemented optical circuits can be assessed through two measures: circuit fidelity and transmission loss. The fidelity is an indication of how close the implemented circuit \( \mathcal{L}_{\text{exp}} \)
FIG. 2. Performance of the device: (a): Target vs measured detection probability for 3 example circuits using the SPAD23 detector array with 12, 18, and 28 outputs. (b): Example implementation of a 38x38 non-unitary target circuit. Each single input to 38 outputs amplitude distribution (corresponding to the lines of the matrix) has been measured separately in a 2-input configuration. The data-sets are re-normalized by their maxima. We measure a statistical fidelity of 98.6%. (c) Fidelity and coupling for 180 randomly distributed unitary circuits in 2x26 input-output configuration. Full line: mean, dashed lines: mean ±1σ. (d): Evolution of both parameters over 10 days without re-calibration. This characterization was done with the camera, in a 2x8 input-output configuration for 160 circuits. The error bars correspond to 1 standard deviation from the mean. Following a single-hour calibration the fidelity and coupling see no significant degradation over the period.

is to the targeted one $L_{\text{target}}$ and is expressed as the trace of the product between the two: $F = \frac{1}{D} \text{Tr}(L_{\exp} L_{\text{target}}^\dagger)$, with D the dimension of $L_{\exp}$. The upper bound of $F$ is one. In practice we record the related statistical fidelity defined as $F = \frac{1}{D} \text{Tr}(||L_{\exp}||L_{\text{target}}|)$ in the output subspace, i.e. when correcting $L_{\exp}$ for global transmission losses through its normalization. In the case of Fig. 2(b), for example we find an average statistical fidelity of 98.6%.

The second measure is the transmission loss of a circuit, defined as the proportion of intensity at the input that is coupled into the targeted output modes. The losses from the input up to the output of the fiber are directly measured using a Thorlabs PM100 power-meter. The SLM introduces losses through several properties. The 95% reflectivity of the screen directly translates into 5% of losses independently of the circuit. However, the losses resulting from its limited fill factor (93%) and diffraction efficiency will change with the displayed phase mask. The power-meter is therefore used to monitor the transmission through the fiber on a circuit-by-circuit basis. The remaining coupling into the output railings is assessed through an initial calibration procedure relating the power-meter and SPAD23 system detection efficiencies (SDE). The ratio between the two SDEs is related to the total number of photons reaching the detector plane for a given measured power on the PM100. As we only have information on the active areas of the SPAD23, this
value is estimated from a fitting procedure on the count rates observed on the detectors. From that fit we obtain the target number of counts that would be measured for a hypothetical detector with 100% fill-factor. We find that the procedure leads to consistent estimations of the ratio between SDEs for various beam waists and angles with 6% standard deviation overall. The last source of loss is due to reflections at every interface and is measured to be 10%. Since the application of anti-reflection coatings would greatly reduce this loss, we provide in table I values both with and without correction from reflection losses.

Following this methodology, we implemented between 100 and 120 unitary circuits $L_k$, randomly chosen from the Haar measure, per input-output setting. For each circuit the statistical fidelity in the output subspace and transmission loss was measured. In practice, the final fine-tuning of parameters was performed such as to maximize the statistical fidelity without correction for transmission losses. This represents the appropriate compromise between circuit fidelity and transmission losses for most applications. However this last optimization can be tuned so as to favour one of the parameters if necessary. The light source used is a superluminescent diode centered on 810 nm, and filtered by a 2 nm FWHM spectral filter. As we use a single input for the characterisation the statistical fidelity in the output subspace and transmission loss was measured. In practice, the final fine-tuning of parameters was performed such as to maximize the statistical fidelity without correction for transmission losses. This represents the appropriate compromise between circuit fidelity and transmission losses for most applications. However this last optimization can be tuned so as to favour one of the parameters if necessary.

Another important aspect of the system is its stability over time. In Fig. 2(d) we plotted the measured fidelity and coupling for a fixed set of 160 2x8 circuits over more than 10 days after a single initial calibration. As one can see, there are variations in quality but no significant degradation over the whole period. These measurements were obtained with the rack set on an optical table with no active vibration system, laminar flow or temperature control in place other than the lab room air conditioning. This level of stability can be therefore expected or exceeded in most settings where quantum sources or detection systems are used. The characterization of the transfer matrix takes about two hours per input mode to perform, meaning that the day-to-day use remains practical even for 8 inputs and beyond.

Two additional properties of the approach distinguish it from integrated alternatives. First, it is largely wavelength agnostic as the system can work over a wide range of wavelengths without specific adaptations, apart from the change of (anti-)reflection coatings and SLM model. Second, the circuit reconfiguration speed is fixed by the refresh rate of the modulator no matter the circuit size. While integrated systems of comparable dimensions typically require reconfiguration time in the order of 1s, the rate is in our case close to 10 Hz. In addition, ongoing developments of the SLM technology hold the promise of significantly faster updating. Commercial models exhibiting 700 Hz of refresh rate are already on the market, and the rate is expected to increase significantly in the future. Two additional properties of the approach distinguish it from integrated alternatives. First, it is largely wavelength agnostic as the system can work over a wide range of wavelengths without specific adaptations, apart from the change of (anti-)reflection coatings and SLM model. Second, the circuit reconfiguration speed is fixed by the refresh rate of the modulator no matter the circuit size. While integrated systems of comparable dimensions typically require reconfiguration time in the order of 1s, the rate is in our case close to 10 Hz. In addition, ongoing developments of the SLM technology hold the promise of significantly faster updating. Commercial models exhibiting 700 Hz of refresh rate are already available while new architectures going to the MHz level have been proposed.

These adaptations would significantly broaden the capabilities of the platform, allowing for example the consecutive application of gates conditioned on the results of preceding ones.
IV. CONCLUSION

In this paper, we have introduced and characterized a compact and linear optical processor based on complex mixing and wavefront shaping. We find that the platform brings significant benefits: advantageous scaling — as exemplified by the realisation of a record 38-output circuit —, high fidelities and competitive reconfiguration rate, while maintaining week-long stability for a 2-inputs, 8-outputs configuration. It represents as such a novel tool for optical QIP that could be used as a convincing alternative or in conjunction with integrated systems.

The asymmetry of the implemented circuits suggests one exciting prospect in particular: the generation of high-dimensional entanglement from few single photon states, thus allowing the interconnection between many quantum platforms.

V. ACKNOWLEDGMENTS

We acknowledge support from EU Horizon 2020 FET-OPEN OPTOLogic (Grant No. 899794).

|                | 2 inputs | 4 inputs | 8 inputs |
|----------------|----------|----------|----------|
| **Fidelity**   | 14 outputs | 97.1% ± 1% | 96.6% ± 1% | 96.3% ± 1% |
|                | 26 outputs | 95.3% ± 1% | 94.7% ± 1% | 94.2% ± 1% |
|                | 38 outputs | 93.7% ± 1% | 93.5% ± 1% | 92.9% ± 1% |
| **Losses**     | 14-38 outputs | 4.0(3.5*)dB ± 0.5dB | 5.1(4.6*)dB ± 1dB | 6.2(5.7*)dB ± 1.2dB |

TABLE I. Measured statistical fidelity and losses for different input-output configurations as measured on the SPAD23 for more than 100 unitary circuits distributed randomly across the Haar measure. *: Values estimated with the addition of anti-reflection coatings.
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