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Abstract

Reconfigurable quantum circuits are fundamental building blocks for the implementation of scalable quantum technologies. Their implementation has been pursued in linear optics through the engineering of sophisticated interferometers [1–3]. While such optical networks have been successful in demonstrating the control of small-scale quantum circuits, scaling up to larger dimension poses significant challenges [4, 5]. Here, we demonstrate a potentially scalable route towards reconfigurable optical networks based on the use of a multimode fibre and advanced wavefront-shaping techniques. We program networks involving spatial and polarisation modes of the fibre and experimentally validate the accuracy and robustness of our approach using two-photon quantum states. In particular, we illustrate the reconfigurability of our platform by emulating a tunable coherent absorption experiment [6]. By demonstrating reliable reprogrammable linear transformations, with the prospect to scale, our results highlight the potential of complex media driven by wavefront shaping for quantum information processing.

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Linear optical networks are prominent candidates for practical quantum computing [1]. The efficient implementation of quantum information processing tasks requires high dimensionality, dense network connectivity and the possibility to actively reconfigure the network. Currently, bulk and integrated linear optics are the most popular platforms to implement such networks. The design of the latter is based on a cascade of beamsplitters and phase-shifters connected by single-mode waveguides [2–5]. However, the scalability of such architecture is significantly limited by the fabrication process. Alternatively, integrated multimode waveguides [7–10] and metasurfaces [11] provided new routes towards robust implementation of larger quantum optical circuits, with the strong disadvantages of not being reprogrammable after fabrication. Coupling spatial modes with other degrees of freedom, such as time, frequency and polarisation [12], provides a different route towards encoding and processing information in higher dimensions [13], but remains an engineering challenge in integrated optics. To date, the quest for a controllable high-dimensional optical network offering arbitrary connectivity is ongoing.

Complex media, from white paint to multimode fibres, can overcome these bottlenecks when used in combination with wavefront shaping. Many classical and quantum applications rely on this approach [14], ranging from spatial mode structuring [15–17] to adaptive quantum optics [18]. As for linear circuits, programmable beamsplitters have been implemented in opaque scattering media [19–21] and multimode fibres [22] through control of spatial mode mixing. In this work, we report the implementation of fully programmable linear optical networks of higher dimensions by harnessing spatial and polarisation mixing processes in a multimode fibre driven by wavefront shaping. We first demonstrate the reliability and versatility of our approach by controlling two-photon interferences between multiple ports of various networks with high accuracy. We then emulate a circuit for tunable coherent absorption, which highlights the reconfigurable nature of our platform. Our work demonstrates the viability of coherent manipulation of optically encoded information via multimode scattering from complex media and wavefront shaping, and its potential for quantum information processing.

The experiment is conceptually illustrated in Fig. 1. The multimode fibre (MMF) is a graded-index fibre supporting ~ 400 propagation modes at $\lambda = 810$ nm. Complex spatial and polarisation mixing occurring in the fibre is the key ingredient that enables the design of a reconfigurable linear transformation $\mathcal{L}$. Indeed, measuring the transmission matrix (TM) of the MMF reveals its highly isotropic connectivity across spatial and polarisation modes (cf. Supplementary Information (SI) Section 1-2). We exploit the connectivity together with the near-unitary of the MMF to program linear optical transformations $\mathcal{L}_i$ (cf. Methods for details) in a four-dimensional Hilbert space defined across spatial and polarisation degrees of freedom, labelled H1, V1, H2, V2.

We demonstrate deterministic manipulation of two-photon interference through a designed optical network $\mathcal{L}_i$. First, we generate a two-photon state by spontaneous parametric down-conversion (SPDC) process (cf. Methods) and guide it to the experimental platform (Fig. 1), in which an optical network $\mathcal{L}$ is encoded using the spatial light modulators (SLM). We implement 4-output $\times$ 2-input optical networks simulating the action of four-dimensional Fourier [23] and Sylvester [24] interferometers (cf. SI Section 4 for definitions). These interferometers are used for certifying indistinguishability between input photons via verifying a suppression criteria [25, 26]. Here, we verify this criteria for a specific two-photon input state by measuring the full set of output two-fold coincidence (Fig. 2). Maximum two-photon visibility values measured after propagating through the MMF (0.96 ± 0.01) and directly at the SPDC source (0.95 ± 0.03) are the same, showing that the platform does not introduce significant temporal distinguishability between photon pairs (cf. SI Section 4). The results show quantum distinctive features: values of the degree of violation $\mathcal{D}$, defined as the probability of occupying two-photon states in all suppression configurations [23, 24], are as small as 0.022 ± 0.009 (Fourier interferometer, for $(1, 3)$ and $(2, 4)$ input pairs) and 0.014 ± 0.008 (Sylvester interferometer, for all input pairs).

Owing to the high number of propagation modes supported by the MMF, we can manipulate phase and amplitude of each element in an optical network independently. To demonstrate this ability, we implement the non-unitary transformation $\mathcal{L}_{\mathrm{N}}$, defined as $\left(\begin{smallmatrix}1 & -1\\ -1 & 1\end{smallmatrix}\right)^{\otimes 2}$, which maps all two-photon interferences into photon anti-coalescences (Fig. 2). The phenomenon presents a distinct result originating from non-unitarity, which derives from information losses stemming from the fact that we do not control all input modes of the MMF. The error between the experimentally synthesised transformation and the theoretically desired one is quantified by $\Delta\mathbb{V} = \langle |V_{ij}^{\mathrm{exp}} - V_{ij}^{\mathrm{th}}| \rangle_{ij}$, where $V_{ij}^{\mathrm{exp(th)}}$ is the experimental (theoretical) visibility over the (i, j) output ports. We measure $\Delta\mathbb{V} = 0.05 \pm 0.04$ on average over all transformations (cf. SI Section 4), thus demonstrating accurate control over 4×2 linear transformations across spatial-polarisation degrees of freedom.

We now illustrate the use of our experimental platform to simulate coherent absorption, an intriguing phenomenon in quantum transport [27]. A typical case is the effect of a lossy beamsplitter on a two-photon N00N state $(s\,|2,0\rangle + e^{2i\phi}\,|0,2\rangle)/\sqrt{2}$. This produces a two-photon absorption probability that depends on the phase ϕ. The phenomenon has been recently demonstrated using a bulk-optics setup with an absorptive graphene layer [27] and a plasmonic metamaterial [28, 29].

In our work, we use our fibre platform to simulate the coherent absorption experiment (Fig. 3a), where the transformation $\mathcal{L}(\phi, \alpha)$ can be seen as a succession of three linear operations: (i) indistinguishable photons are sent onto a beamsplitter to generate a N00N state (N=2) with a controllable output phase ϕ; (ii) the N00N state interacts with a lossy phase-tunable beamsplitter (LTBS). The matrix that describes the action of the LTBS is $t\left(\begin{smallmatrix} 1 & e^{i\alpha} \\ e^{i\alpha} & 1 \end{smallmatrix}\right)$ where $t \leq 0.5$ is the transmission coefficient and α is a fully tunable phase [27]; (iii) the two output ports of the LTBS are distributed into four output ports by two balanced beamsplitters in order to measure two-photon survival probability. This overall survival probability is defined as a sum of probabilities of detecting two photons in all possible output combinations of the LTBS, i.e., both photons on either ports (up or down) or one photon at each port.

As shown in Fig. 3b, the effect of coherent absorption is maximised for $\alpha = p\pi, p \in \mathbb{Z}$ (red line). In the case where the relative phase $\phi = q\pi, q \in \mathbb{Z}$, which corresponds to having a state $(|2,0\rangle + |0,2\rangle)/\sqrt{2}$ as input, the output state is a superposition of vacuum- and two-photon state and the probability of one-photon transmitting to the targeted outputs is null. This result hence exhibits the non-linear behaviour of the two-photon absorption in the quantum regime. On the other hand, when $\phi = q\pi + \pi/2$, thus corresponding to an input state $(|2,0\rangle - |0,2\rangle)/\sqrt{2}$, only single-photon loss occurs (cf. SI Section 5 for details). Owing to our ability of fully control the relative phase α (Fig. 3c), which is a significant step forward with respect to previous experimental arrangements [27–29], we observe a transition of the coherent absorption phenomenon from unitary $\alpha = q\pi + \pi/2$ (blue dots) to the maximal coherent absorption situation $\alpha = \pi$ (red dots).

Partial control, which is usually deleterious for a quantum system, here provides the ability to coherently control the interaction in a non-unitary way, which can be exploited for processing tasks [30]. Note that, as the optical system (SLM and MMF) is nearly loss-less, and non-unitarity in our experiment originates from the fact that we control only half of the propagation modes of the MMF in each input port (cf. SI Section 3 for explanation). The unmonitored modes thus embody a sink where information about the desired optical network leaks, resulting in effective open system dynamics of the latter. The total energy transmittance $2|t|^2$ to all targeted outputs of the optical network $\mathcal{L}_i$ reaches 0.45(0.5) experimentally (theoretically), which is close to the maximum transmission of the LTBS.

The dimensionality of our platform can in principle be scaled up, as the main limiting factor in our experimental implementation is given by the detection architecture. A significantly larger network can be managed, for instance, by replacing our detection apparatus with an array of correlation detectors [31]. In Fig. 4, we experimentally showcase the scalability of our platform by designing a larger optical network with 18 targeted outputs allocated arbitrarily at different positions and taking arbitrary polarisation on the EMCCD camera. In SI Section 3, we discuss the fidelity, scalability and programmability of this optical network architecture.

We report the use of a multimode fibre to implement fully programmable linear optical networks across spatial and polarisation degrees of freedom. This platform harnesses the highly complex coupling between a large number of modes of the MMF, thanks to the ability to spatially control the input light wavefront. We successfully programmed this platform to implement circuits able to tackle certification tasks all the way up to the emulation of coherent absorption. We thus demonstrate the versatility and full reconfigurability of our approach, including the management of different degrees of freedom of the propagating light. Complex mixing occurring in an optical mixer, in general, can go beyond path and polarisation reported in this work. Spectral, temporal, and spatial (radial and orbital angular momentum) degrees of freedom can also be manipulated [14, 16]. We anticipate that our architecture can be applied to those degrees of freedom. We also highlight its scaling potential by demonstrating control over up to 18 output ports, whereas the number of input ports can also be scaled well beyond 2, provided a multi-photon source is available. Our architecture provides an efficient and scalable alternative to integrated circuits for linear quantum networks.

METHODS

Two-photon source

The frequency-degenerate photon pairs are produced from a type-II polarisation-separable collinear spontaneous parametric down-conversion (SPDC) source (Fig. 1a), using a 10-mm periodically poled potassium titanyl phosphate crystal (ppKTP) pumped by a single-mode continuous-wave laser in a single spatial mode configuration. The photon pairs transmit through a spectral filter ($\lambda = 810 \pm 5$ nm) and are separated by a polarising beamsplitter. The indistinguishability of photon pairs is controlled by a temporal delay δ. The photon pairs are then prepared in the same horizontal polarisation, and collected with polarisation-maintaining single-mode fibres, which are then connected to the MMF platform. A coincidence window is set at 2.5 ns for all experiments. All coincidence counts are corrected for accidental coincidence counts.

Network programming

After the TM acquisition using a phase-shifting holographic technique with a co-propagating reference [32] (cf. SI Section 1), a given linear transformation $\mathcal{L}_i$ (network) is programmed. The input electric fields $\tilde{E}_{\text{in}}^{(j)}$ and the corresponding SLM phase pattern for each j-th input port is calculated by solving an inverse scattering problem $\tilde{E}_{\text{in}}^{(j)} = \mathrm{T}^{(j)\dagger}\mathcal{L}_i^{(j)}$, where $\mathrm{T}^{(j)}$ is the sub-part of the measured TM linking the relevant input modes for each j-th input port to the targeted output modes. Imperfections in generating the input electric fields $\tilde{E}_{\text{in}}$ with the spatial light modulator (SLM) lead to errors in the coefficients of the linear transformation $\mathcal{L}_i$. In the case of our first experiment (the control of two-photon interference), we additionally performed an amplitude correction when a new $\mathcal{L}_i$ is programmed by adjusting on the amplitudes of the co-propagating reference fields. This was done by means of minimising the mean squared error between implemented amplitudes and desired ones. For the experiment on the control of the coherent absorption, we compensated the amplitude variations using the normalised second-order correlation function $g^{(2)}$.

DATA AVAILABILITY STATEMENT

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

CODE AVAILABILITY STATEMENT

The code for data analysis and simulation that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

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STATEMENT OF AUTHOR CONTRIBUTION

SL, TJ, HD carried out the experiment and the analysis of the data, SL LI performed numerical simulations and LI, AF, MP provided a theoretical analysis of the results. SL proposed the coherent absorption experiment. SG proposed the original idea and supervised the project. All authors discussed the implementation, the experimental data and the results. All authors contributed to writing the paper.

FIGURE CAPTIONS

FIG. 1. Multimode-fibre based programmable linear-optical network (a) Conceptual schematics of the apparatus. Photon pairs produced by spontaneous parametric down-conversion (SPDC) are injected into a multimode fibre (MMF) along orthogonal polarisation using spatial light modulators (SLMs). We use commercial MMF (Thorlabs, GIF50C) as a tool to achieve mode mixing. The transmission matrix (TM) is measured across spatial and polarisation modes of the MMF (cf.SI Section I). The wavefront corresponding to a desired linear transformation $\mathcal{L}_i$ is calculated and displayed on the SLMs (cf. Methods). Output ports of interest are selected by two single-mode fibre-based polarisation beamsplitters (fPBS) mounted on translation stages. These correspond to two spatial modes and two polarisations labelled as (H1, V1, H2, V2). Light is detected by avalanche photodiodes (APDs) connected to a coincidence electronics. The output plane of the MMF is imaged onto an electron multiplying charge-coupled device (EMCCD) camera along both polarisations (H and V). (b) An arbitrary 4×2 linear network $\mathcal{L}_i$ is implemented by shaping the spatial phases of each input port H_{in} and V_{in}. For each input, the predicted output fields after propagation through the MMF are shown. We observe that light is focused into the four targeted output ports with the desired amplitudes and phases. (L: lenses, F: filter, HWP: half wave plate, PBS: polarising beamsplitter, D: Iris diaphragm, FM: Flip Mirror, WP: Wollaston prism, BS: beamsplitter.)

FIG. 2. Control of two-photon interference among spatial-polarisation degrees of freedom (a) Two-photon interference: fitting (solid lines) and experiment (dots) for Fourier $\mathcal{L}_{\mathrm{F}}^{(1,2)}$, Sylvester $\mathcal{L}_{\mathrm{Sy}}^{(1,2)}$, and non-unitary $\mathcal{L}_{\mathrm{N}}^{(1,2)}$ transformations where the two-photon state is coupled to the (1,2) input pair. (b) Visibility pattern of four-dimensional Fourier (F), Sylvester (Sy) and non-unitary (N) transformation for all input-output combinations. This corresponds to 18 balanced 4x2 optical networks with fully controllable phase relations.

FIG. 3. Controlled coherent absorption (a) The linear network $\mathcal{L}(\phi, \alpha)$ programmed in the MMF (Fig.1) emulates the following circuit: Photon pair enters a Mach-Zehnder (MZ) interferometer composed of a balanced beamsplitter and a lossy balanced phase-tunable beamsplitter (LTBS). Both the phase ϕ between the two arms and the phase α of the LTBS can be tuned at will. Light in each output port of the MZ interferometer is analysed via two balanced beamsplitters preceding an array of four photocounters to measure the probability of two-photon survival at the targeted output ports. (b) Probability of two-photon survival at the targeted outputs: theory (solid lines) and experiment (dots). The blue dots are for $\alpha = \pi/2$, corresponding to an emulated lossless MZ interferometer. The corresponding probability of two-photon survival is independent of ϕ. The red dots are for $\alpha = \pi$, corresponding to a lossy beamsplitter in which the probability of two-photon survival depends on the relative phase ϕ. (c) Probability of two-photon survival as a function of ϕ and α, showing a transition from emulated lossless to lossy LTBS.

FIG. 4. Intensity image of a high-dimensional linear-optical network on the EMCCD. The SPDC light from both inputs is simultaneously distributed into 18 targeted outputs, 9 in each polarisation (H: Horizontal; V: Vertical).