Studying Open Scattering Channels in an Analog Physical Simulation

(Student paper)

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We simulate a small multiple-scattering system with an 12x12 programmable integrated photonic processor on which we encode the full scattering matrix of the system, acting as an analog and physical simulation device. We show that we can measure the singular value distribution of transmission efficiencies of a 6-channel scattering system in this way. Already the raw data gets close to the predicted bimodal distribution.
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INTRODUCTION

Scattering waves are found in many places in nature and technology. Unraveling their physics is important for understanding transport of both electrons, phonons of photons through disordered media. Many of their properties can be described by random matrix theory [Bee1997], alhtough it turns out to be difficult to match some of the more striking predictions of that theory to experiments. For instance, the theory predicts that the transmission through disordered systems is dominated by nontransmiting channels and -counterintuitively- by some near-perfect transmitting channels, also known as 'closed' and 'open channels', respectively [Rot2017]. This bimodal behavior of the transmission eigenvalues [Do1982, Mel1988] underlies many different phenomena, such as electronic conductance fluctuations, suppression of electronic shot noise and increased optical transmission through random disordered systems. Despite the central role of open channels in scattering physics, only indirect evidence for their existence has been reported. Measuring the entire bimodal transmission is impossible in electronics because of the small size of electrons. In free-space optics it is a challenge, since one needs to resolve all the modes of the transmission matrix describing the system [Goe2013].

In random matrix theory, the system-specific details are replaced by a unitary scattering matrix

$$\mathbf{S} = \begin{pmatrix} \mathbf{R} & \mathbf{T} \\ \mathbf{T}' & \mathbf{R}' \end{pmatrix},$$

where the submatrices **T** and **R** are the transmission and reflection matrices, respectively. This scattering matrix contains the appropriate statistical properties of the system, while remaining agnostic to the microscopic details of the scatterer. This allows to study their physics on any system that captures these statistics.

We use the approach of random matrix theory to physically simulate our diffusive system on a state-of-the-art 12-mode one-way integrated photonic processor, shown in the inset of Fig. 1a) and schematically in Fig. 1b). The processor is a commercial SiN integrated photonic system, on which more details can be found in [Tab2021]. On this network, an entire scattering matrix **S** is implemented using the Clements decomposition of an arbitrary unitary into a network of programmable beam splitters [Cle2016]. The first six output modes are treated as 'reflection' modes and output modes 7-12 as transmission modes. Compared to traditional scattering systems in, the advantage of the integrated photonic processor is that the channels are discrete single-mode fiber inputs and outputs, avoiding problems with finite numerical aperture of input and output optics. It also avoids the problem of over or under sampling of the input and output fields [Pai2020].

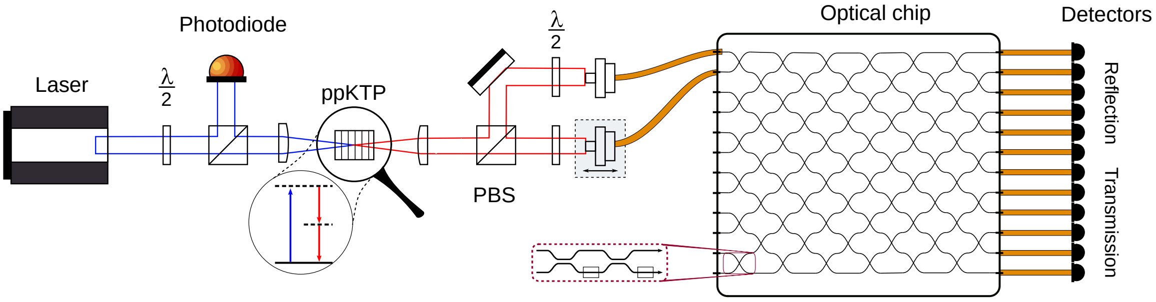

Fig. 1. The setup for characterization of the artificial scattering system: On the left is the Spontaneous Parametric Down-Conversion (SPDC) source injecting pairs of photons into the 12x12 programmable optical processor that acts as the scattering system. Since the chip does not reflect any light, output modes are assigned as reflection or transmission channels, so that a full scattering matrix of a 6-channel scattering system can be simulated.

After programming a scattering matrix in the processor, we characterize this system as if it were an unknown scattering system as described further down. We measure and extract the 6x6 transmission matrix **T**. From this, six singular values can be found by standard singular-value decomposition. By itself, six singular values are not sufficient to build up a smooth singular value distribution to compare meaningfully to theory. A major advantage of this network is, however, that it is fully reconfigurable. It is therefore straightforward to program different matrices. We implemented a total of 200 randomly generated scattering matrices. These scattering matrices are generated by a numerical simulation of a 6-mode scattering system with appropriate settings. The simulation of the 12-mode S-matrices follows the model as proposed by Dorokhov, Mello, Pereira and Kumar [Do1982, Mel1988], which divides the scattering system into short segments. Each segment is shorter than the transport mean free path and longer than the wavelength. Adding a new segment can now be described as a perturbative correction [Rot2017]. We follow the method of Ko and Inkson [Ko1988]. The matrices are computed by simulating a one-dimensional 6-mode waveguide with perfectly reflecting boundaries. The waveguide is divided into 40 equally sized sections over the length of the waveguide. Each section has a probability of 10% to have a scatterer placed at a random coordinate inside this waveguide segment, corresponding to the weak scattering regime. Furthermore, given the transport mean free path, the number of segments N determines the average transmission efficiency. We chose $N = 40$ and $\langle T \rangle = 0.37$, allowing us to observe open channels with 200 random instances of these waveguides. Stronger-scattering waveguides, i.e. with more segments and scatterers, have lower average transmission such that an insufficient number of singular values can be sampled to resolve the open channels.

Matrix characterisation

Characterisation of the matrices on the network is performed by sending pairs of single photons into the network and sampling their output distribution with a battery of superconducting nanowire single-photon detectors (SNSPDs). Although it would in principle be possible to characterise the matrix with classical coherent light in an interferometrically stable setup, performing the readout with single photons has the advantage that we do not need interferometric stability of the fibers connecting the PIC network with the outside world [Lai2012, Dha2016], because of the phase insensitivity of the single-photon quantum state. Hence, our quantum readout is more robust than the equivalent classical method.

The matrix amplitudes are sampled by sequentially injecting single photons into each input mode and measuring the output distribution. The photon flux is corrected for known experimental fluctuations such as the variations of pump power over time, relative detector efficiencies, and fiber-to-chip coupling losses. The phases of the matrix elements are characterized by sequentially measuring two-photon interference in the network for a given set of combinations of two input and two output modes [Lai2012].

To reduce experimental measurement time, we only characterized the phases of six input modes to all 12 output modes. The matrix amplitudes are measured for the entire **S** matrix so that the 1-photon output distribution can be normalised.

RESULTS

First results are shown in Fig. 2, where the singular value distributions of the transmission matrix without any further processing is plotted. Contrary to data with traditional scattering media or multimode fibers, already the raw data show a shoulder indictive of the expected bimodal distribution. The non-physical data points at $\tau^2 > 1$ are caused by measurement noise such as dark counts, imperfect control of the chip, multiphoton states and detector blinding (nonlinear loss).

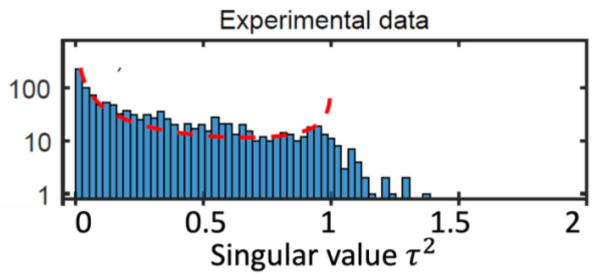

Fig. 2. The singular values distribution of the transmission matrix for a data set of 200 matrices. The red dashed line is the theoretical distribution as predicted by [Goe2013]. The non-physical values higher than 1 result from residual measurement noise.

DISCUSSION

It is slightly unsatisfying that notwithstanding the exquisite control over this system, the raw data does not convincingly show the bimodal distribution. However, we think imposing the reasonable condition that the system does not exhibit gain should be enough to bring forth the bimodal distribution, without imposing the much more stringent unitarity condition. To the best of our knowledge, the bimodal distribution has never been seen without imposing unitarity, which will already lead to a bimodal distribution of the singular value distribution of random Gaussian matrices.

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