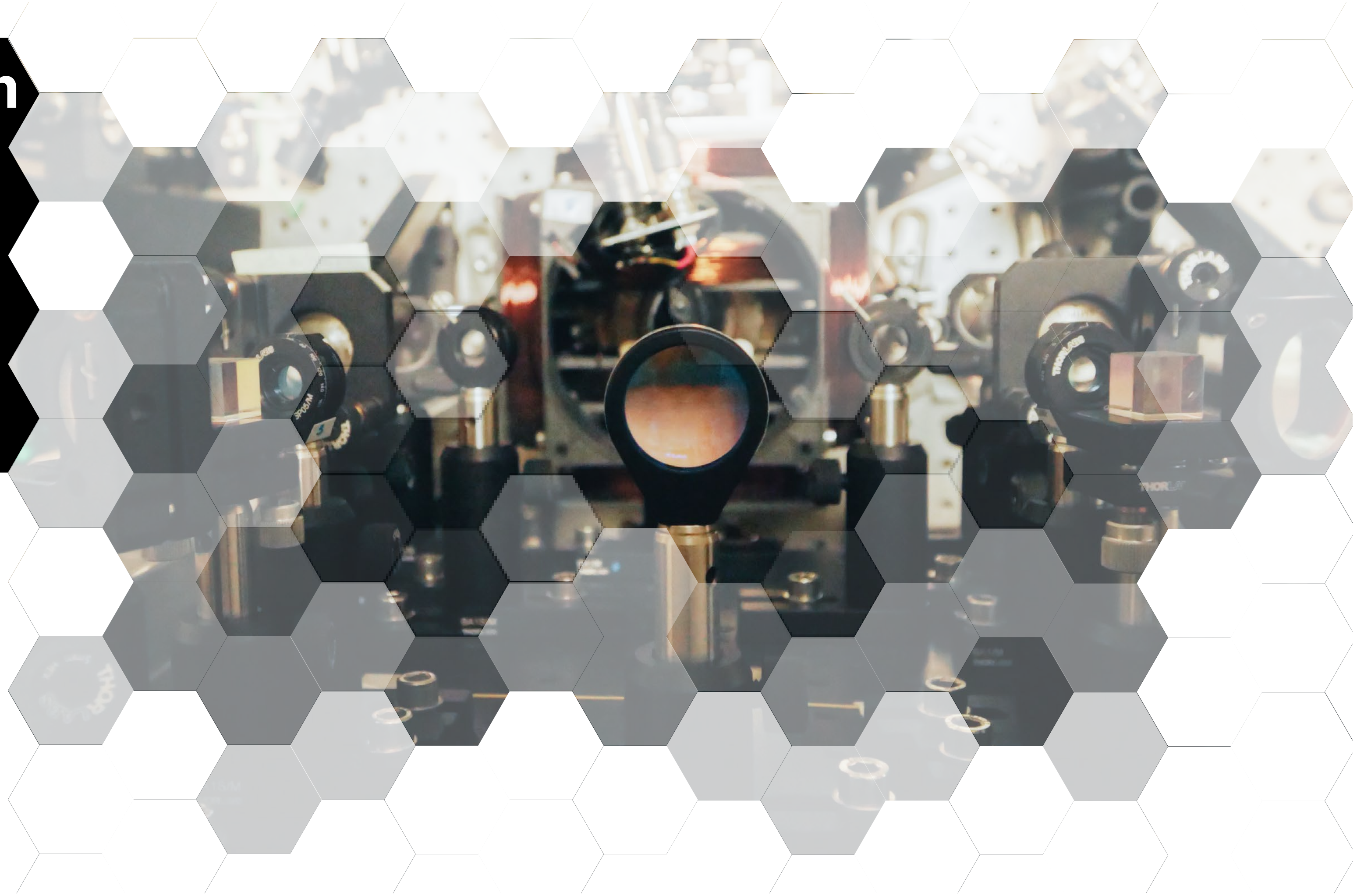
Dyakonov Ivan

Quantum Technology Center



Linear optical platform for quantum computing in Quantum technology centre

Lomonosov Moscow State University

Faculty of physics

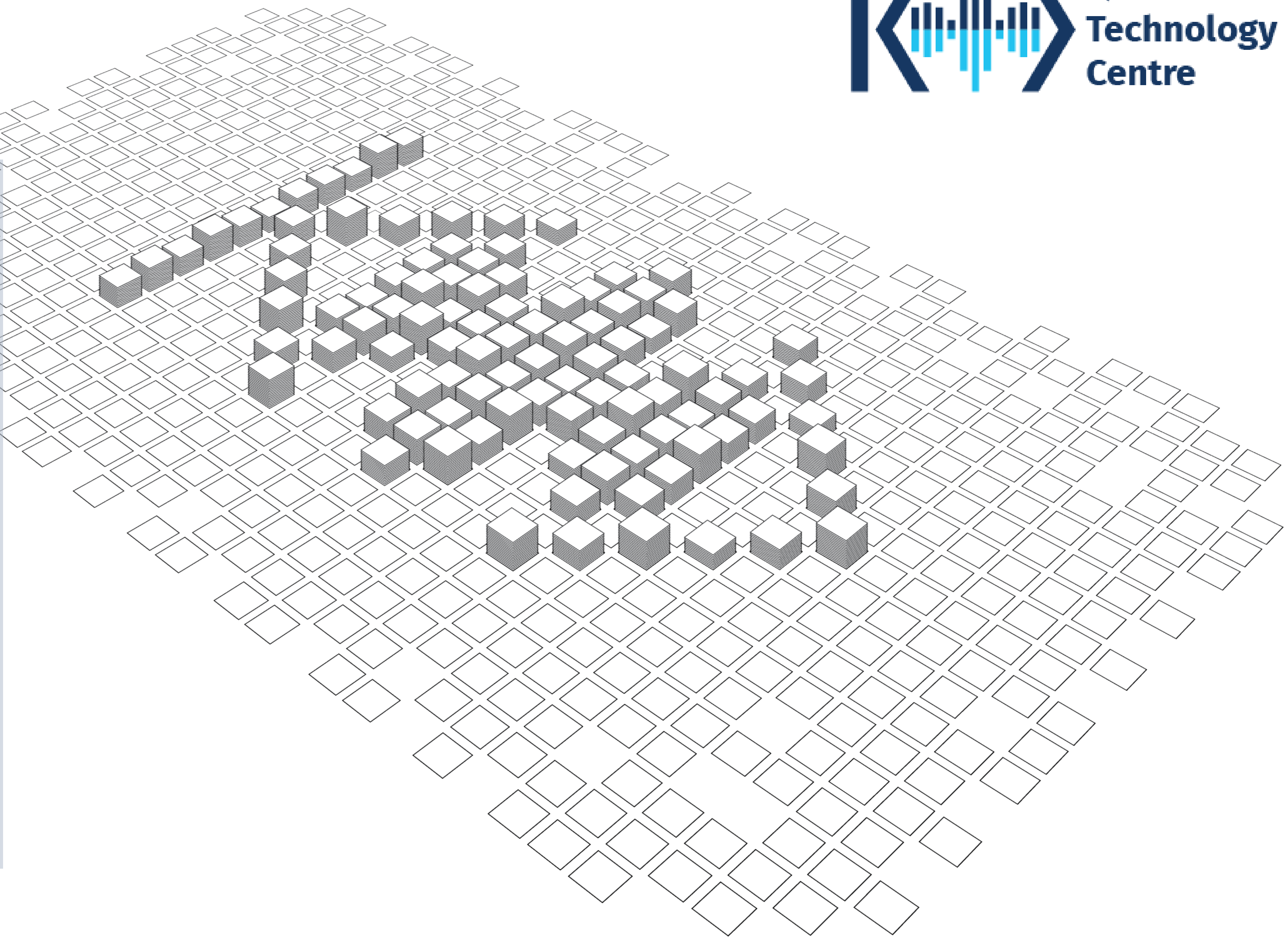
Chair of quantum electronics

Quantum Technology Centre

Founded in 2017

Research areas:

- quantum communication
- quantum computing
- atomic physics
- quantum optics
- integrated photonics
- nanophotonics and metamaterials
- single-electron physics

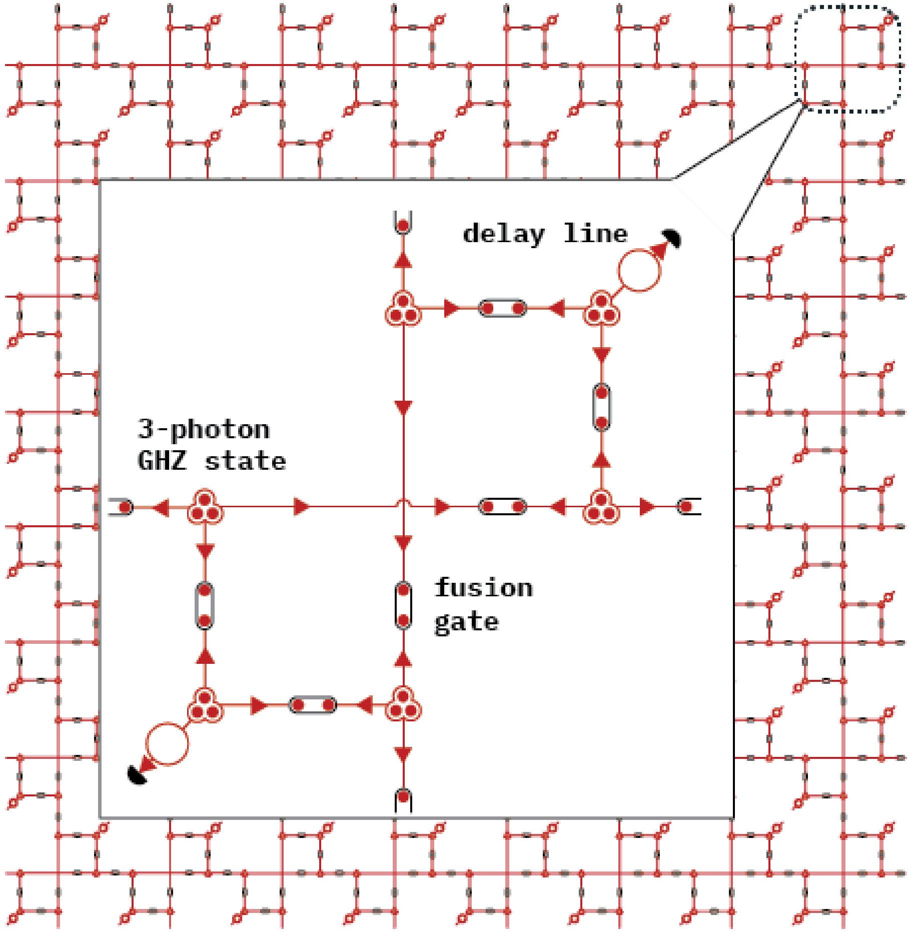


Linear optical quantum computing

Linear optical quantum computing

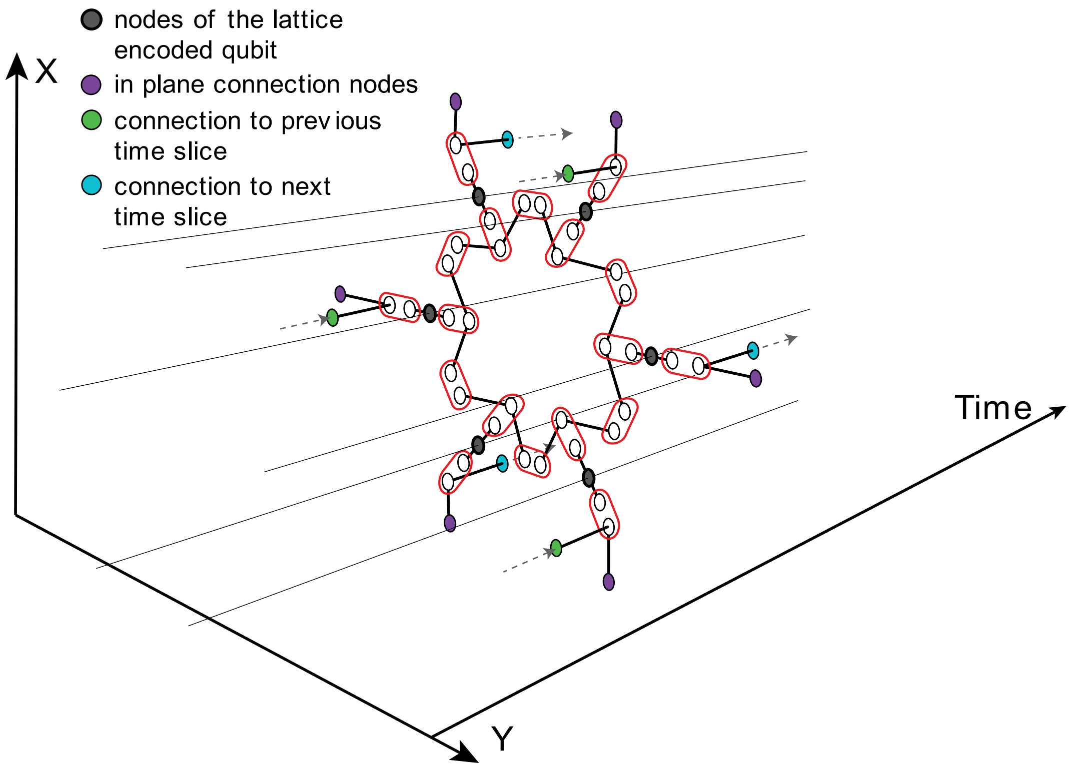
Near-term architecture

Long-term architecture

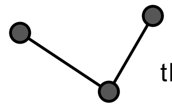


Linear optical quantum computing

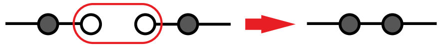
BLUEPRINT



Initial resource

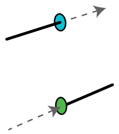


Fusion gates



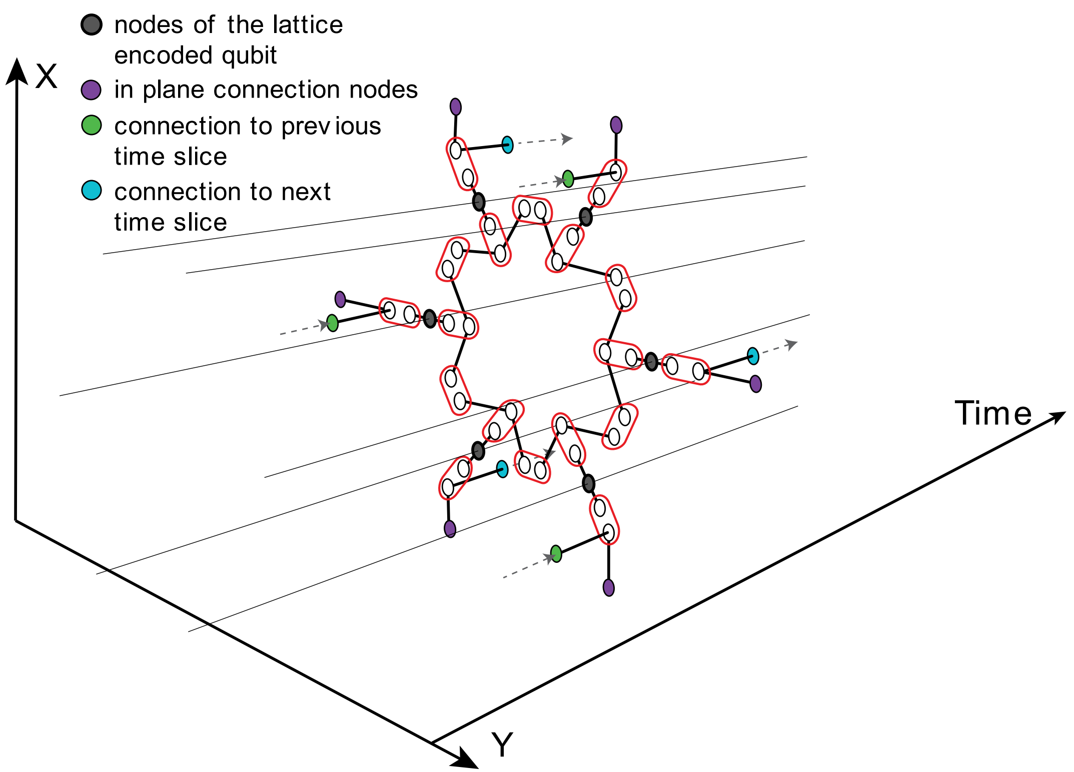
Boosted type-II fusion gate
with single-photon ancillae

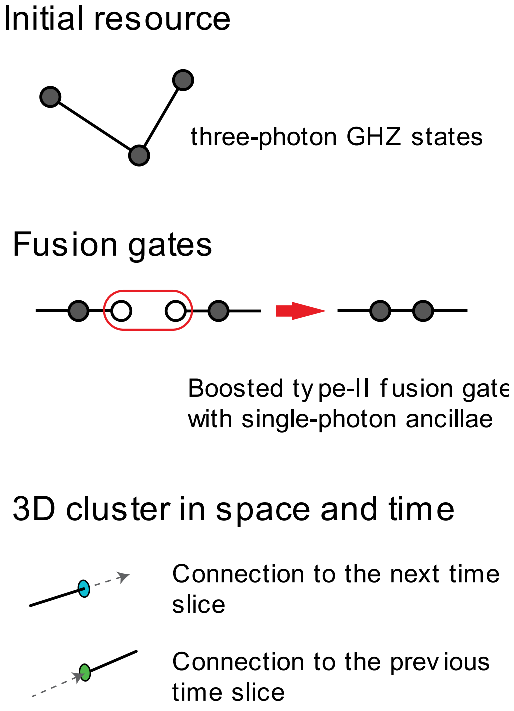
3D cluster in space and time



Linear optical quantum computing

BLUEPRINT





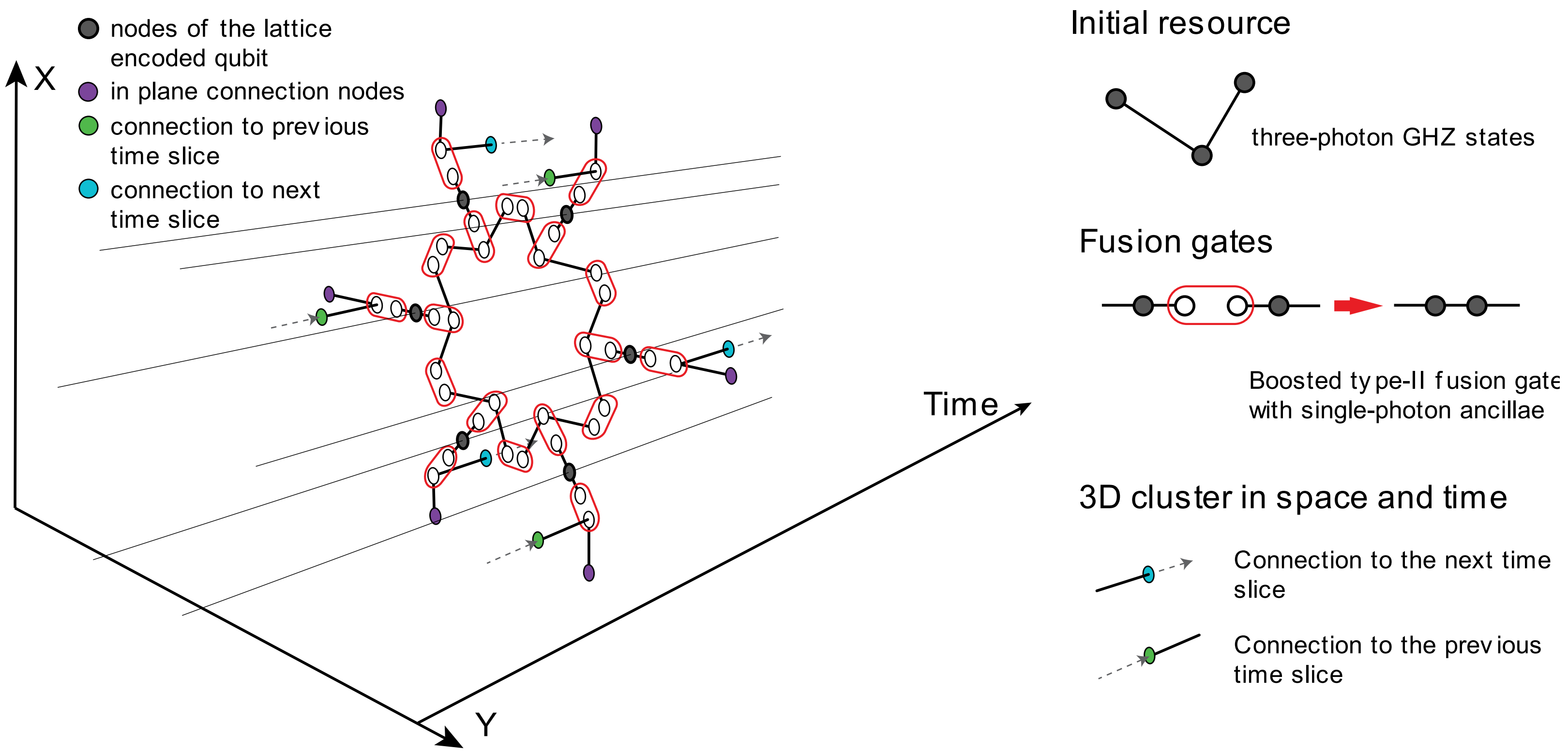
- single-photon source + entangling gates

or

- entangled photon source

Linear optical quantum computing

BLUEPRINT



- single-photon source + entangling gates

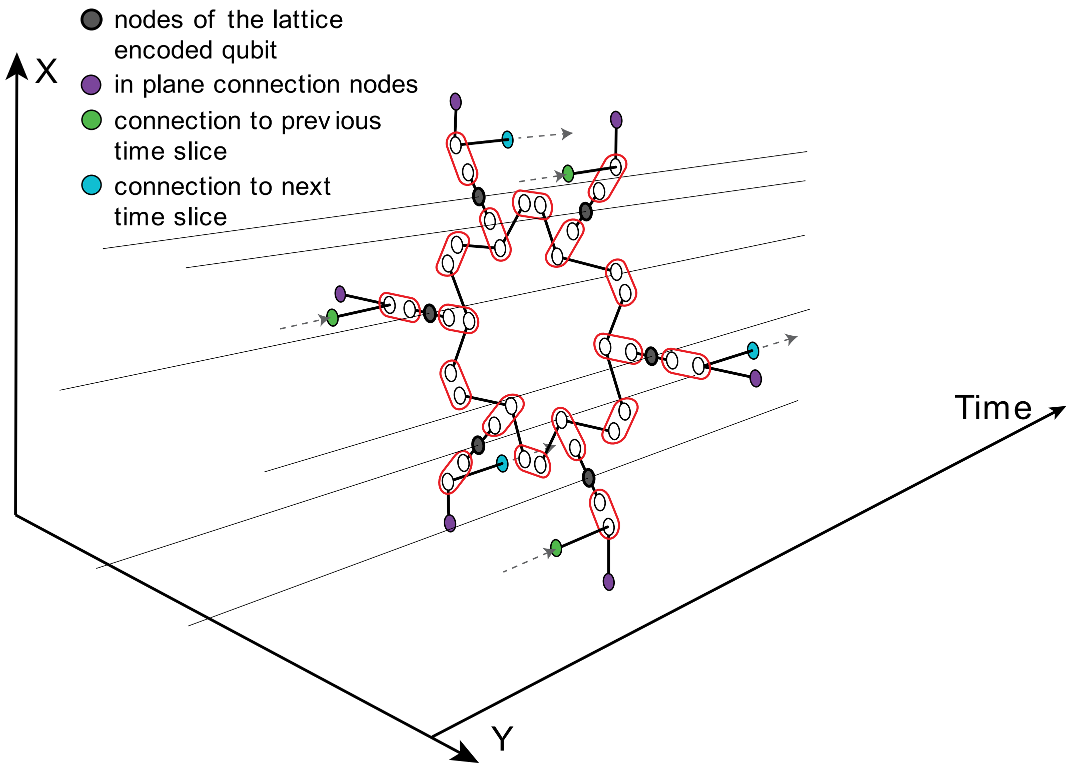
or

- entangled photon source

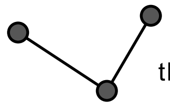
- optical circuitry
- photon-number resolving detectors

Linear optical quantum computing

BLUEPRINT

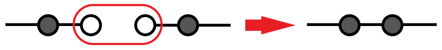


Initial resource



three-photon GHZ states

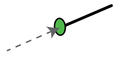
Fusion gates



Boosted type-II fusion gate with single-photon ancillae

3D cluster in space and time

Connection to the next time slice



Connection to the previous time slice

- single-photon source + entangling gates

or

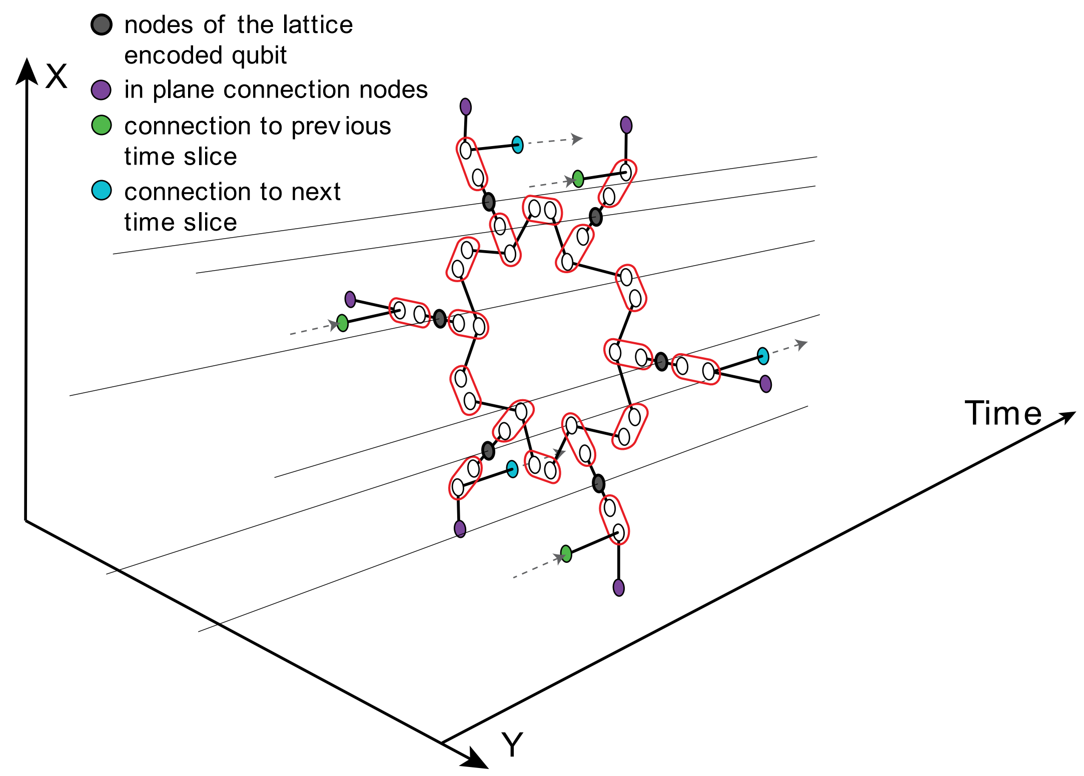
- entangled photon source

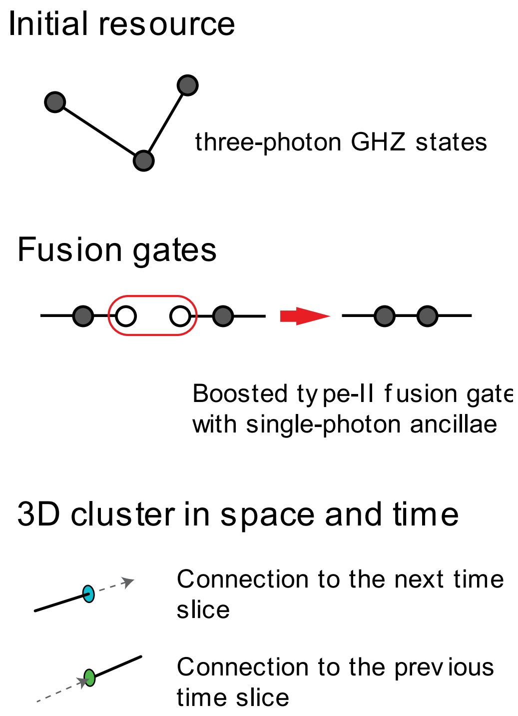
- optical circuitry
- photon-number resolving detectors

- low-loss delay lines

Linear optical quantum computing

BLUEPRINT





- single-photon source + entangling gates

or

- entangled photon source

- optical circuitry
- photon-number resolving detectors

- low-loss delay lines

- high-speed electronics
- fast optical switches

Our lab

Optical circuits

- design
- technology
  - femtosecond laser writing
  - lithography

Sources

- Quandela QD source
- 10-channel demux
- 6-photon SPDC

Detectors

Installed 24 SNSPDs

Theory

- Heralded gate optimization

Our lab

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Theory

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OPTICAL CIRCUITS. TECHNOLOGY

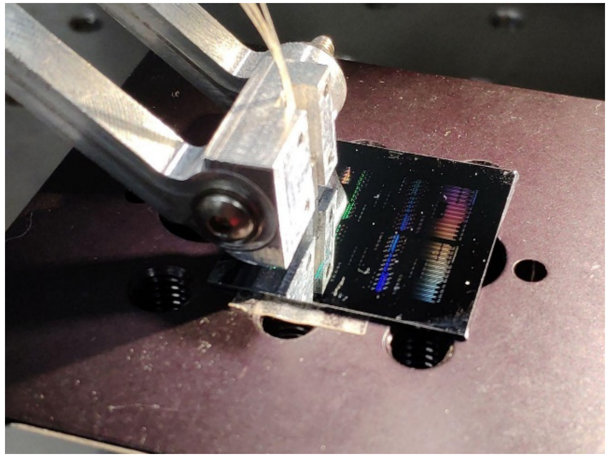
Advanced Nanofabrication

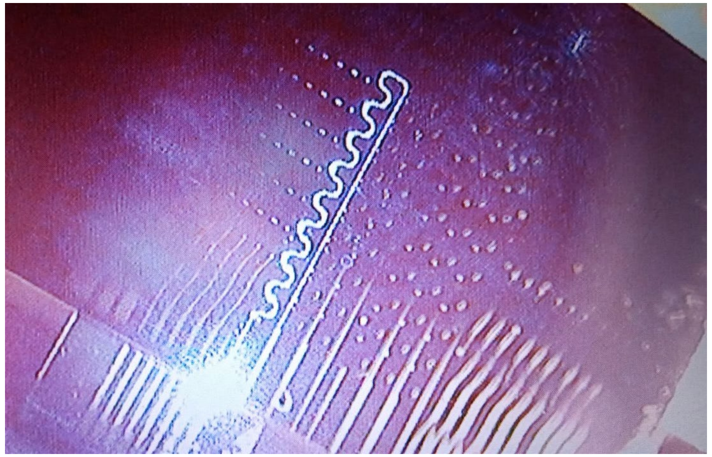
FMN Laboratory
Bauman Moscow State Technical University
fmn.bmstu.ru/en

Optical circuits fabrication

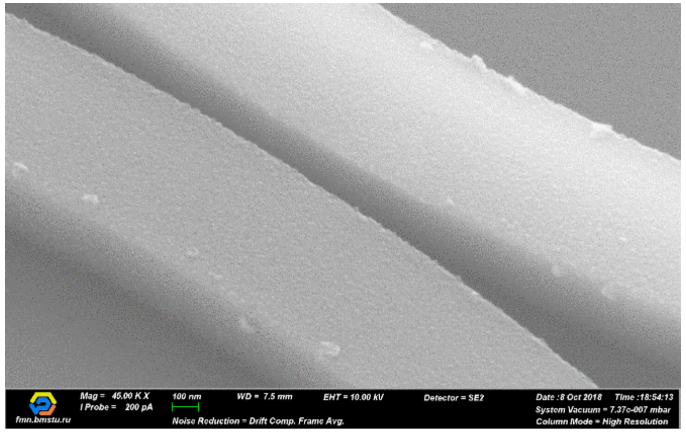
- **Silicon nitride SM waveguides**
  < 1 dB/cm @ 925 nm
- **Grating couplers**
  < 5 dB @ 925 nm, TE, 0 deg
- **Edge couplers**
  < 3 dB @ 925 nm

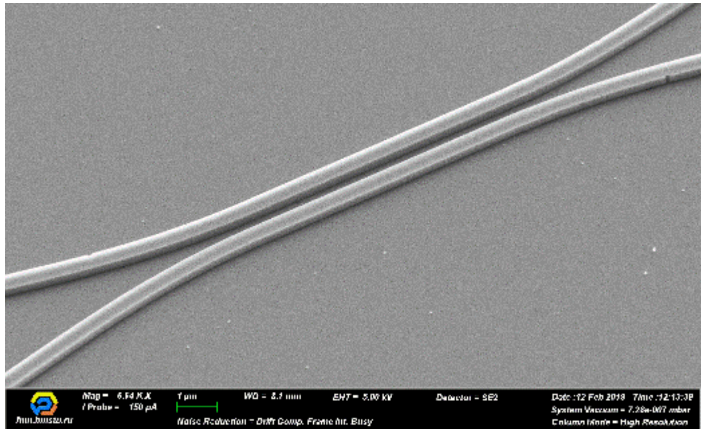
SiN integrated photonics

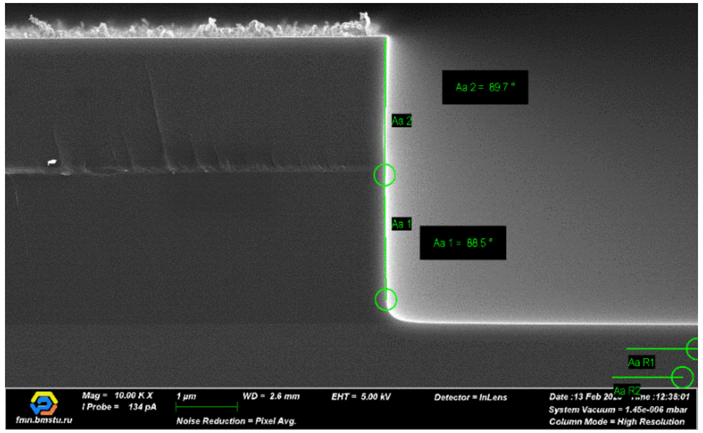




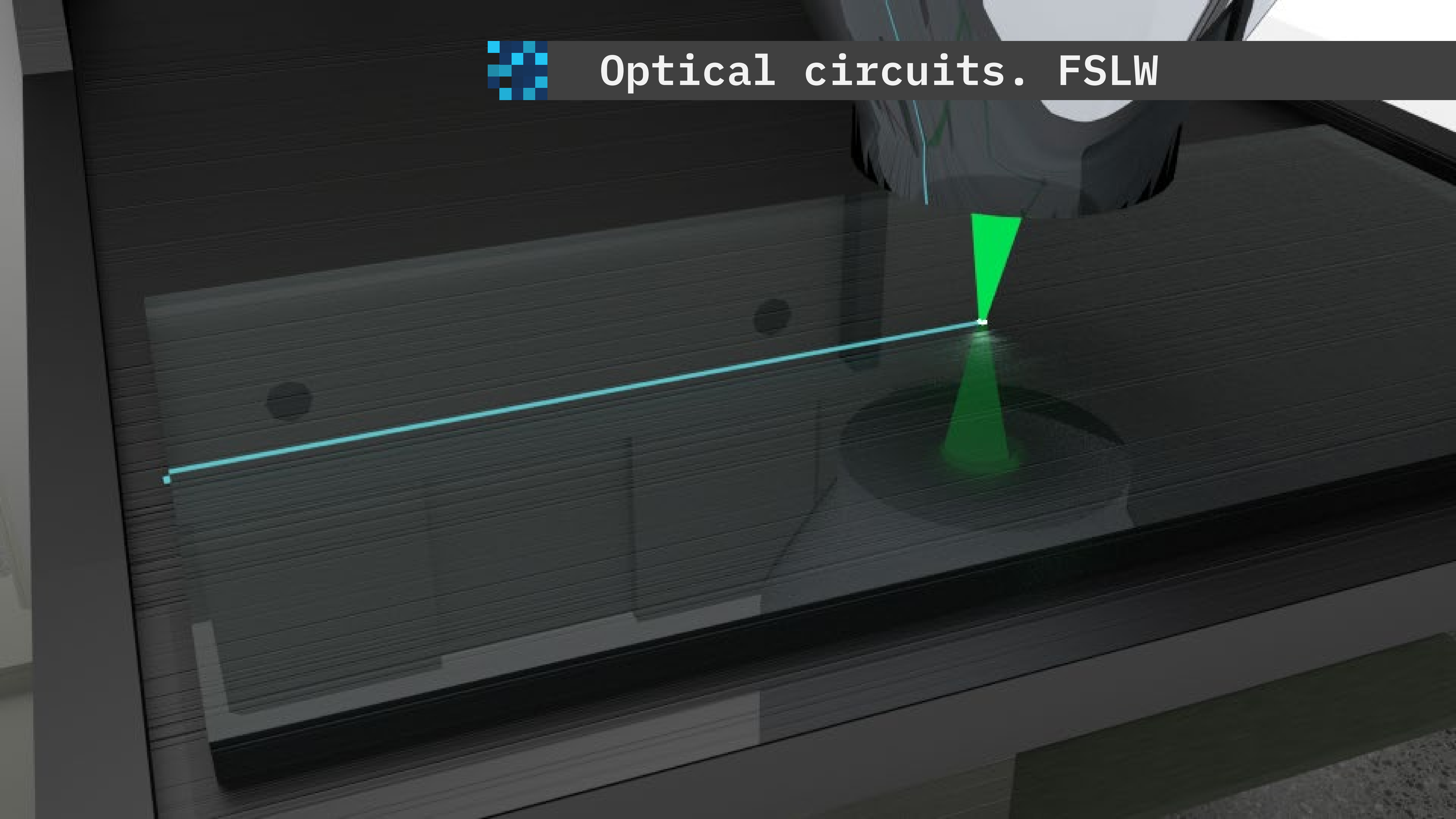
- Directional couplers loss below 0.2 dB
- Y-splitters loss below 0.2 dB
- Thermo-optically tunable phase shifters



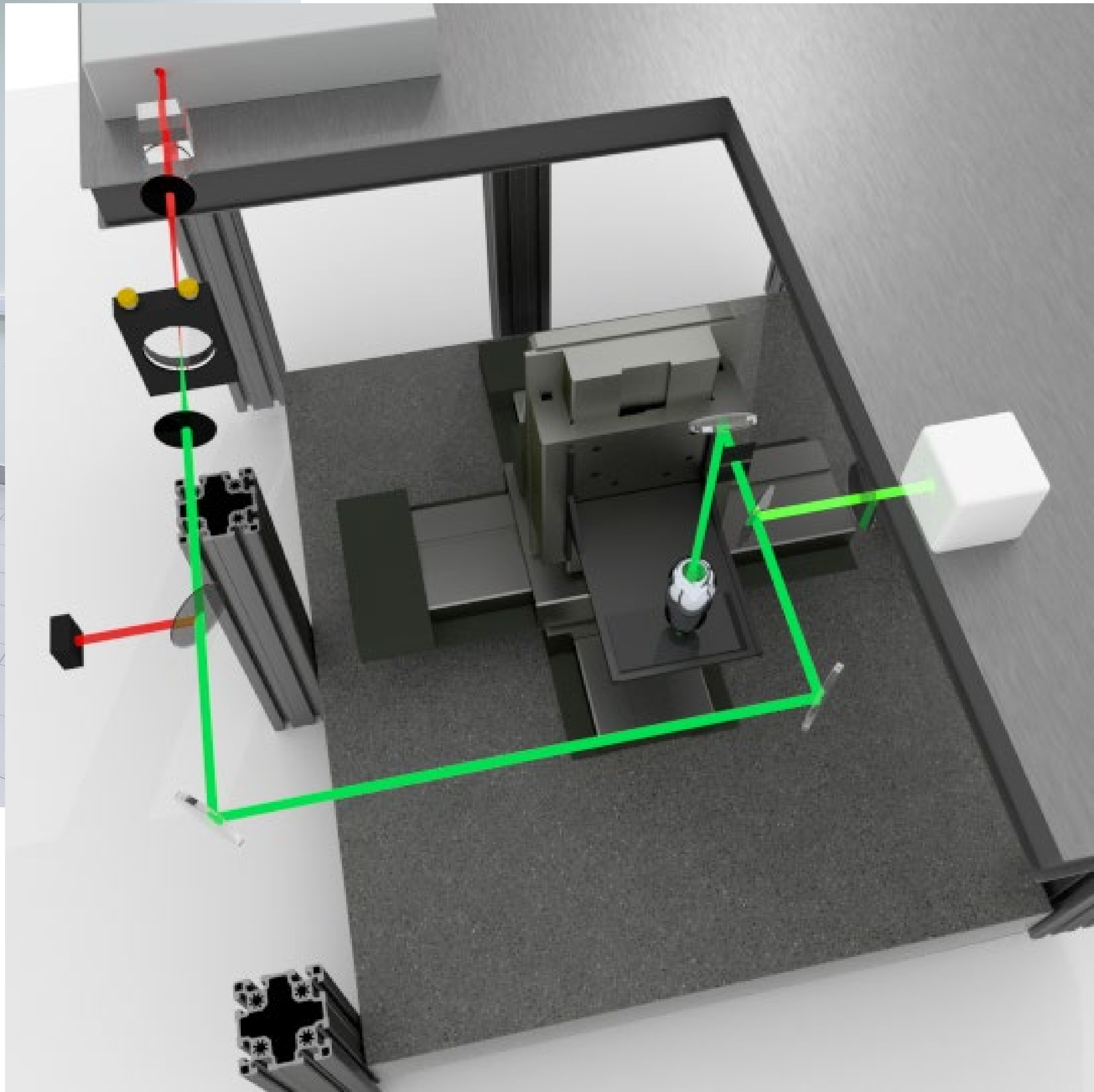




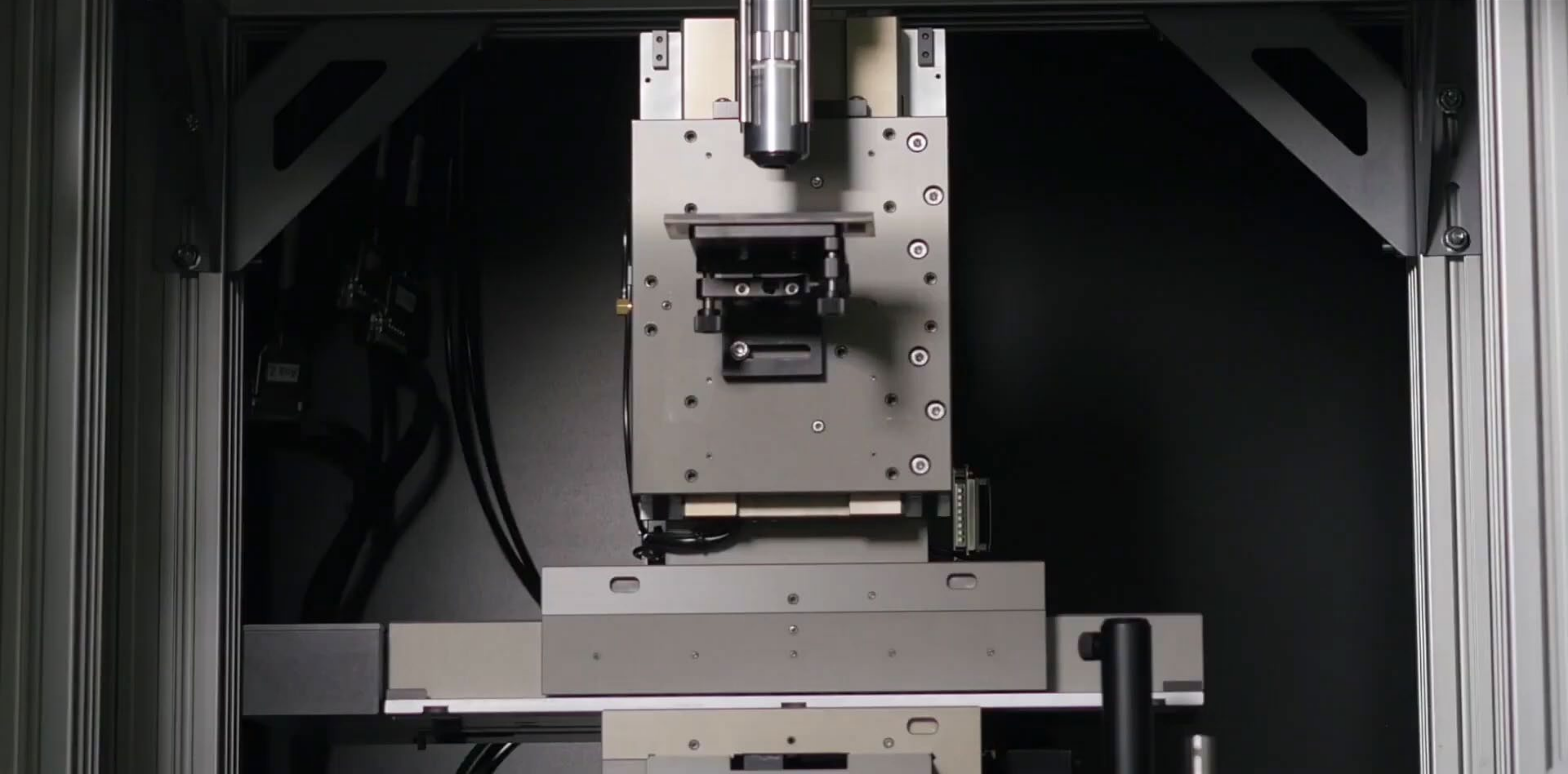
Optical circuits. FSLW



Femtosecond laser writing

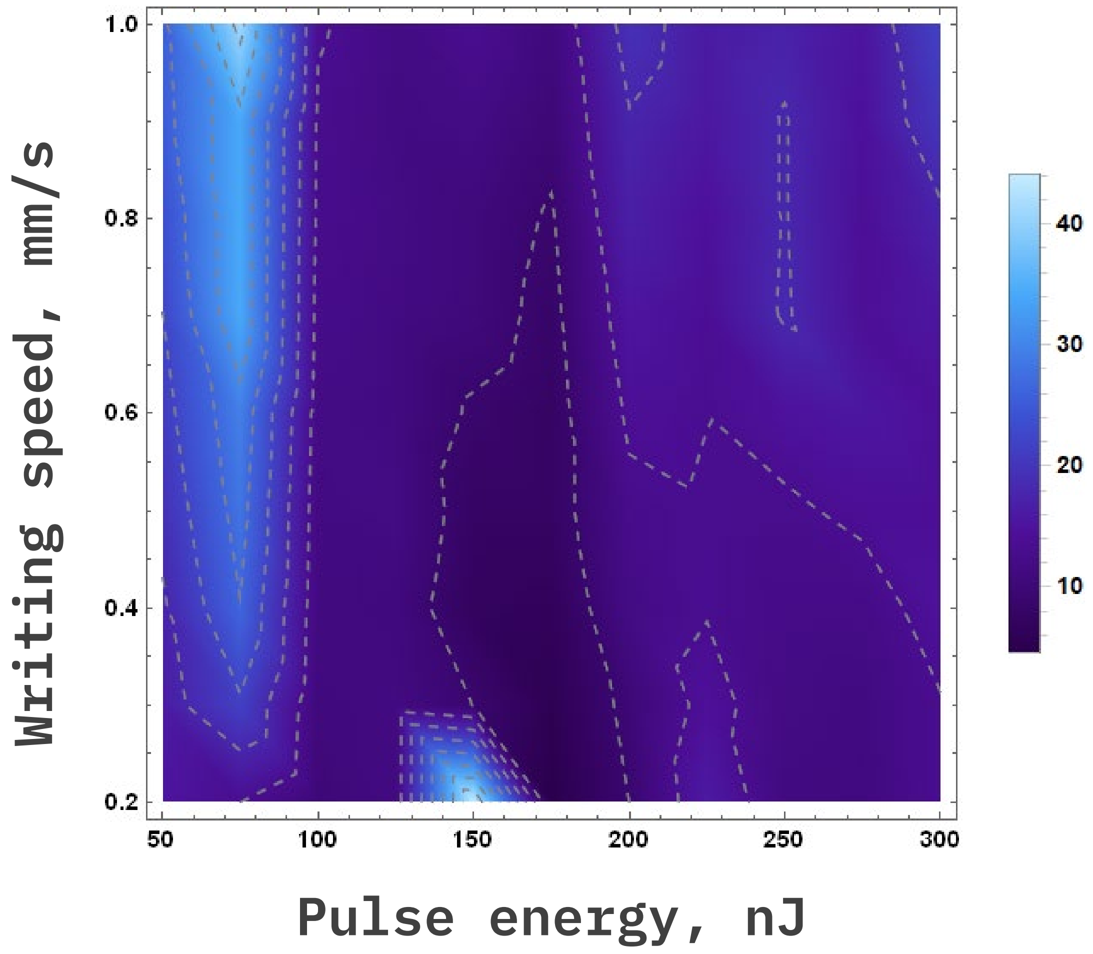


Femtosecond laser writing

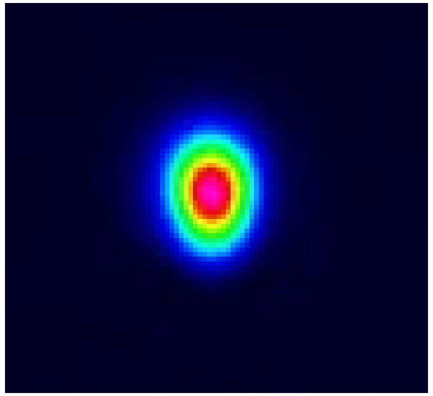


Waveguides

Parameter map



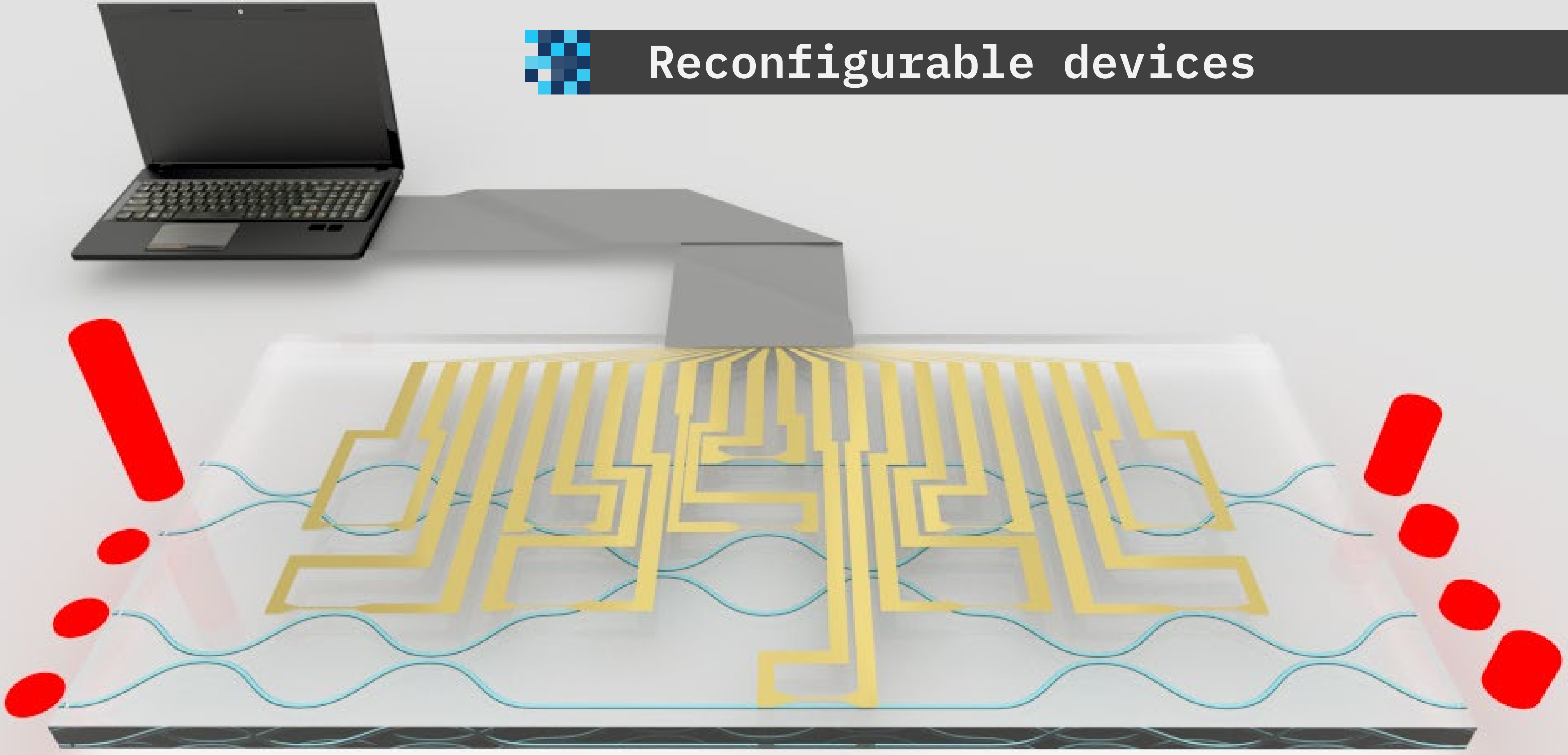
Characteristics



Negligible induced anisotropy

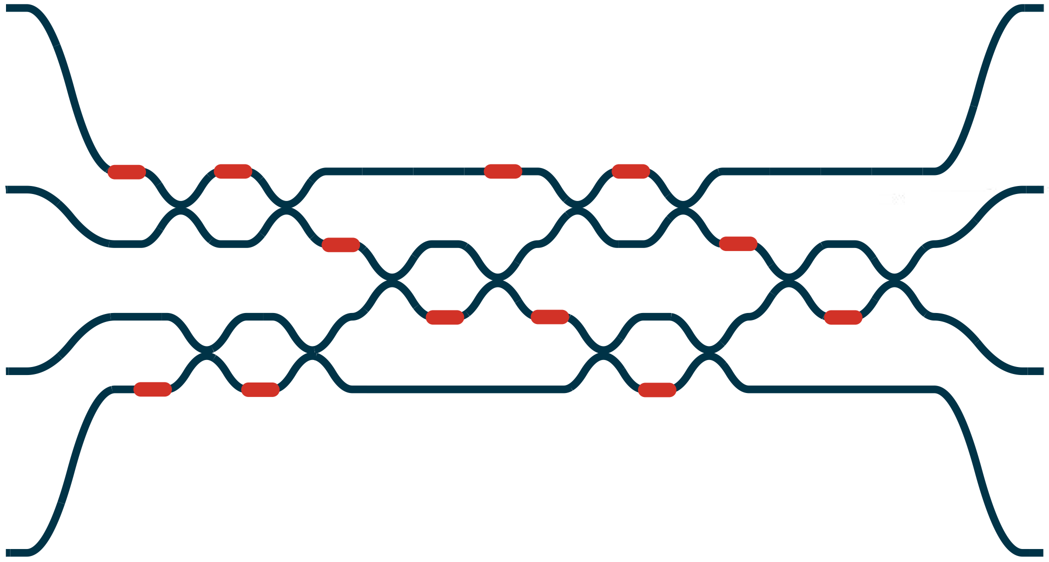
- Propagation loss – 0.2 dB/cm
- Coupling loss – 1 dB per facet (SMF @ 808 nm)
- Bending loss:
  - 0.1 dB/cm (50 mm radius)
  - 0.8 dB/cm (80 mm radius)

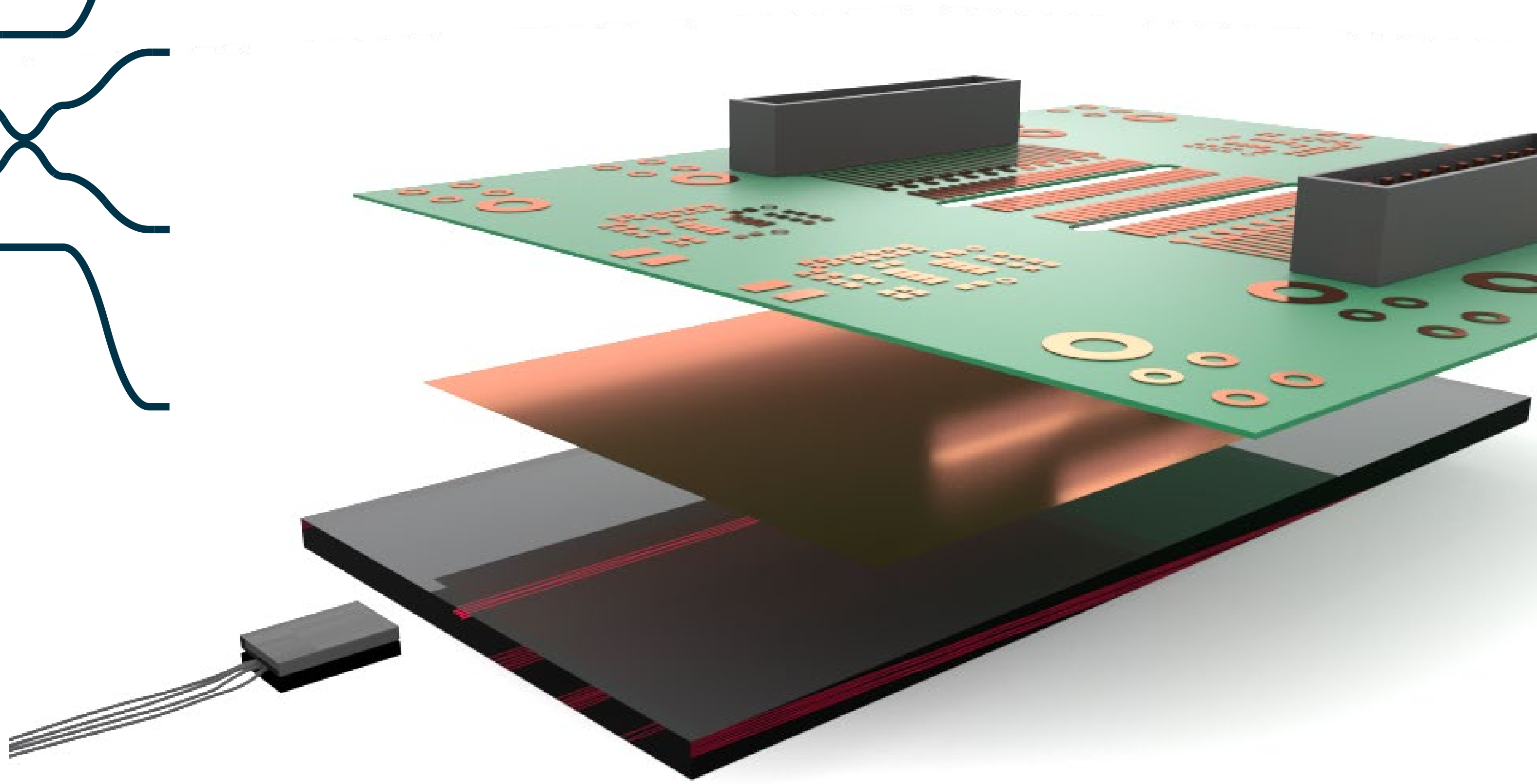
Reconfigurable devices



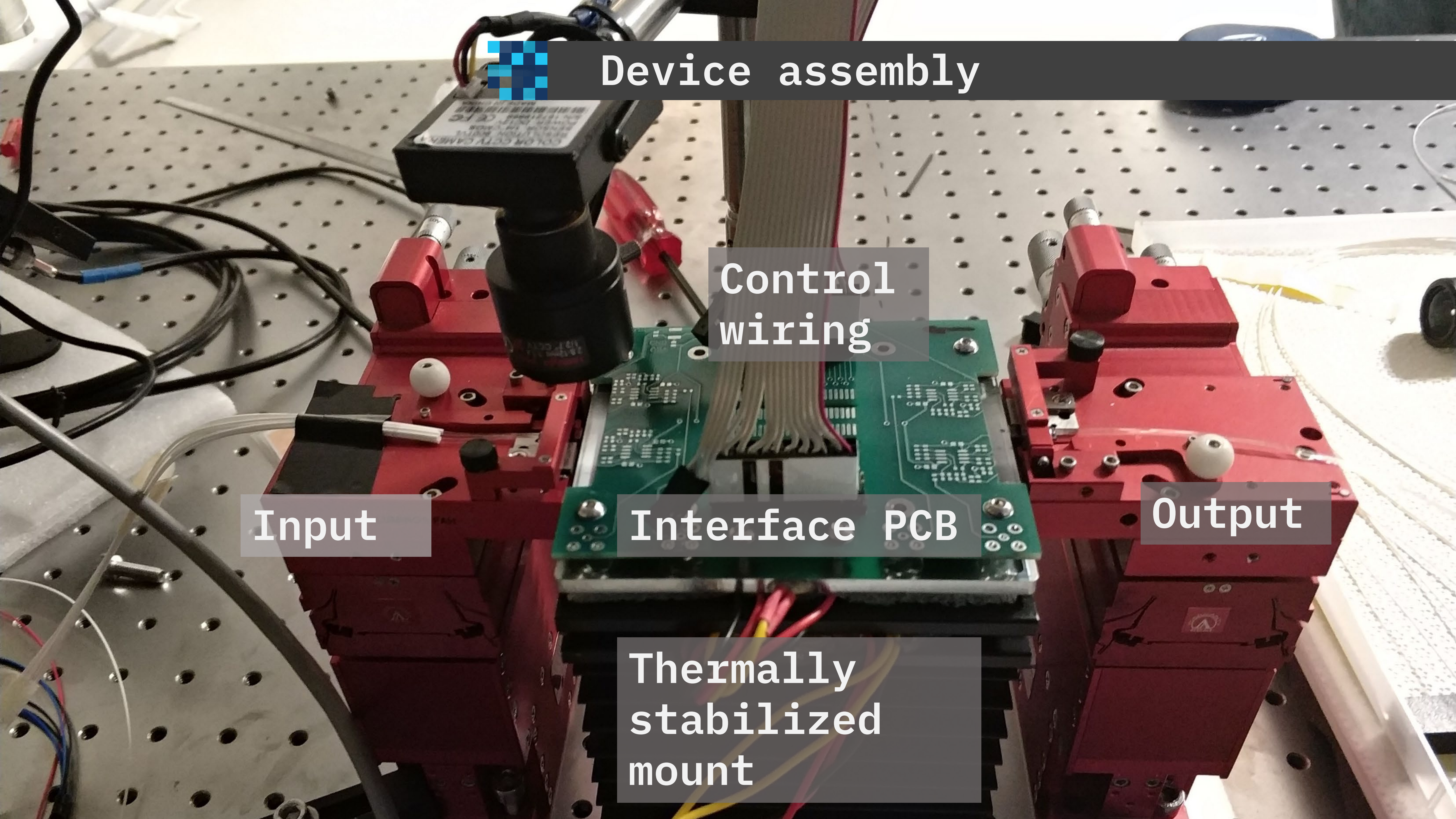
Reconfigurable devices

4x4 universal linear circuit





Device assembly



Device tuning

Problems: large thermal crosstalk and imperfect couplers

Tuning procedure:

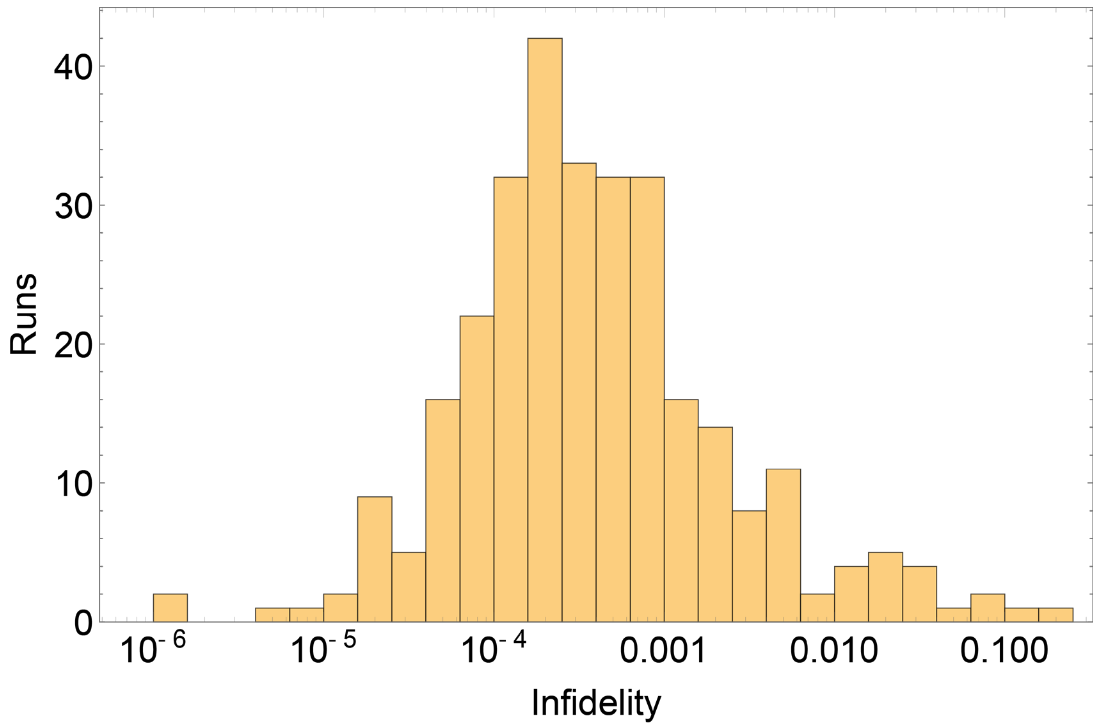
1. Generate the output distribution $\{\tilde{S}_j\}$, $\sum \tilde{S}_j = 1$
2. Measure output intensities I_j on each step
3. Subtract the background and normalize

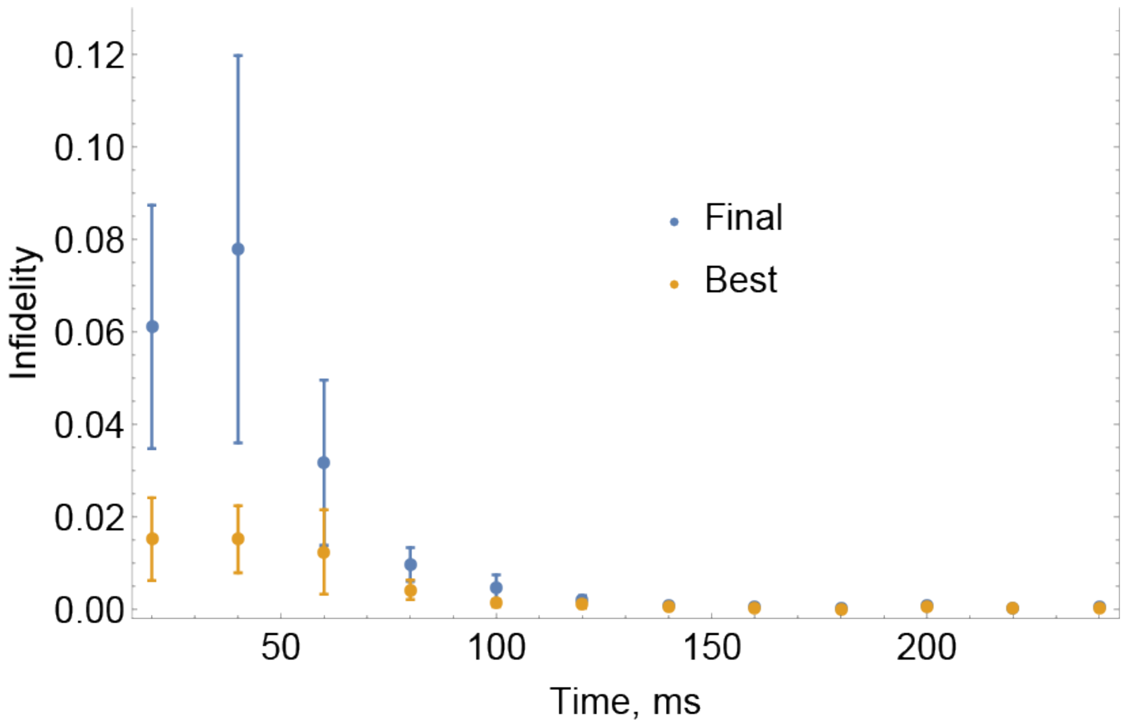
$$S_j = \frac{I_j - I_{bg}}{\sum (I_j - I_{bg})}$$

4. Adjust the phases in order to minimize

$$1 - F = 1 - \left(\sum \sqrt{S_j \tilde{S}_j} \right)^2$$

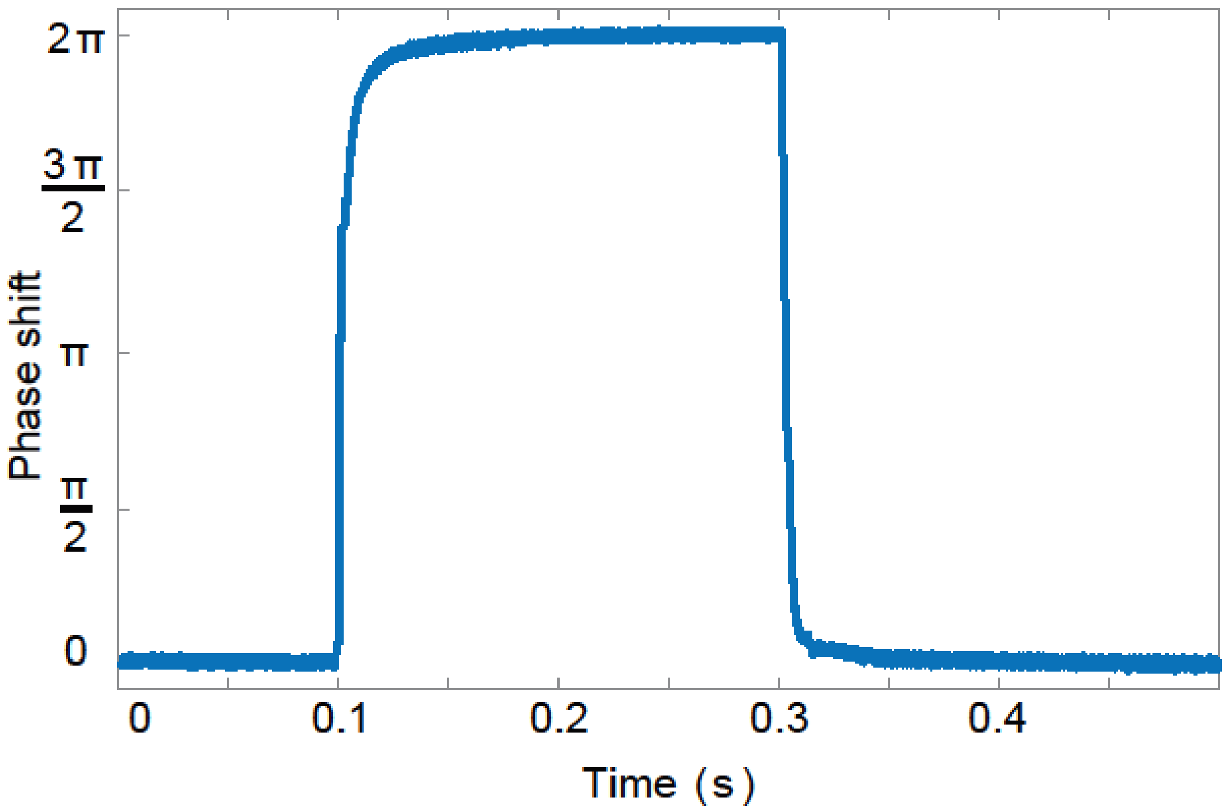
Device tuning

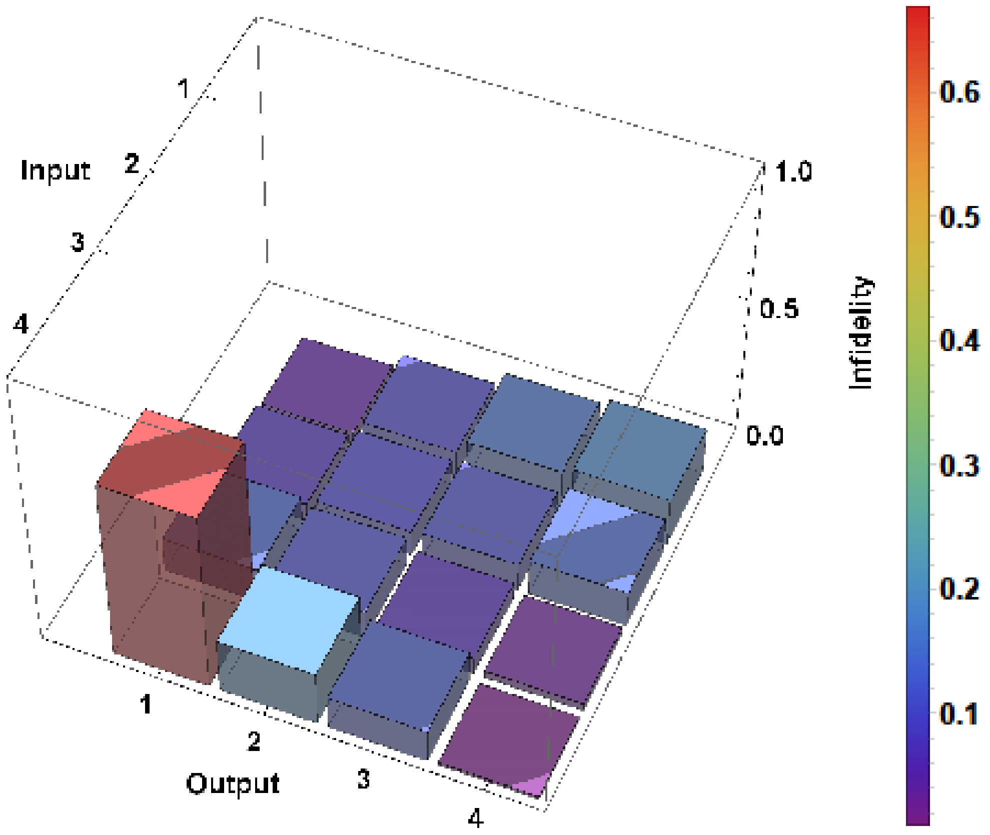




I.V. Dyakonov et al. Phys. Rev. Applied 10, 044048 (2018)

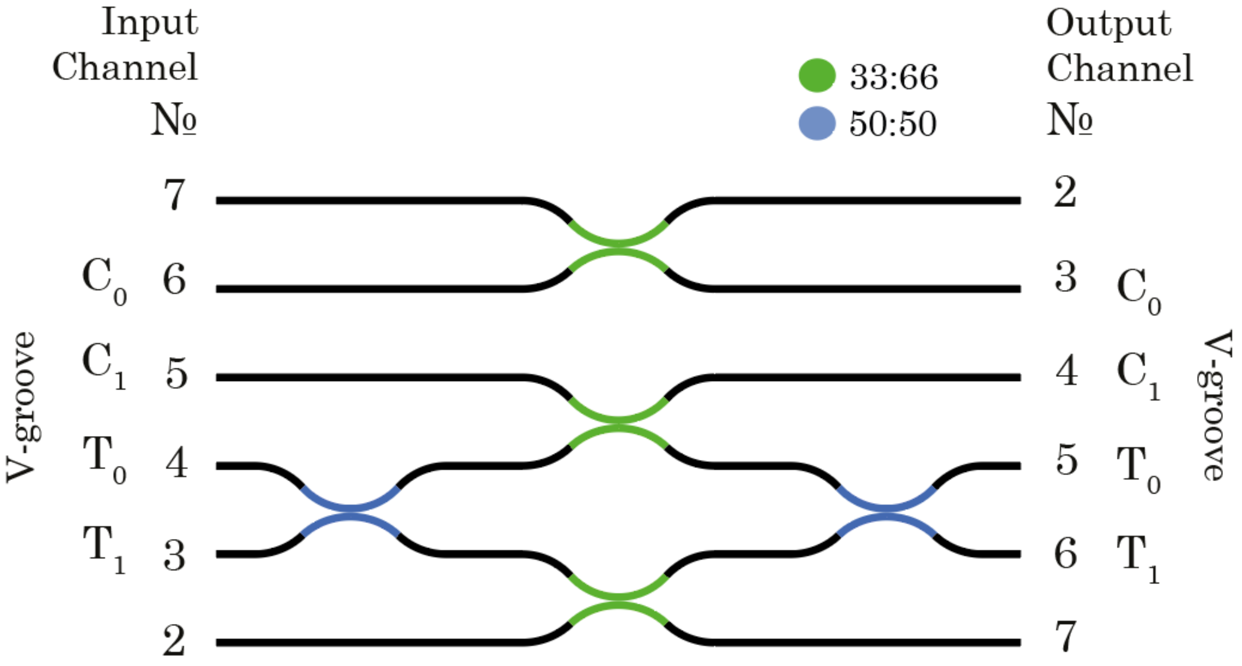
Device tuning. Switching





Two-qubit gate

	00	01	10	11
00	0.0033	0.1258	0	0
01	0.1102	0.03	0	0
10	0	0	0.1048	0.0201
11	0	0	0.0365	0.1042



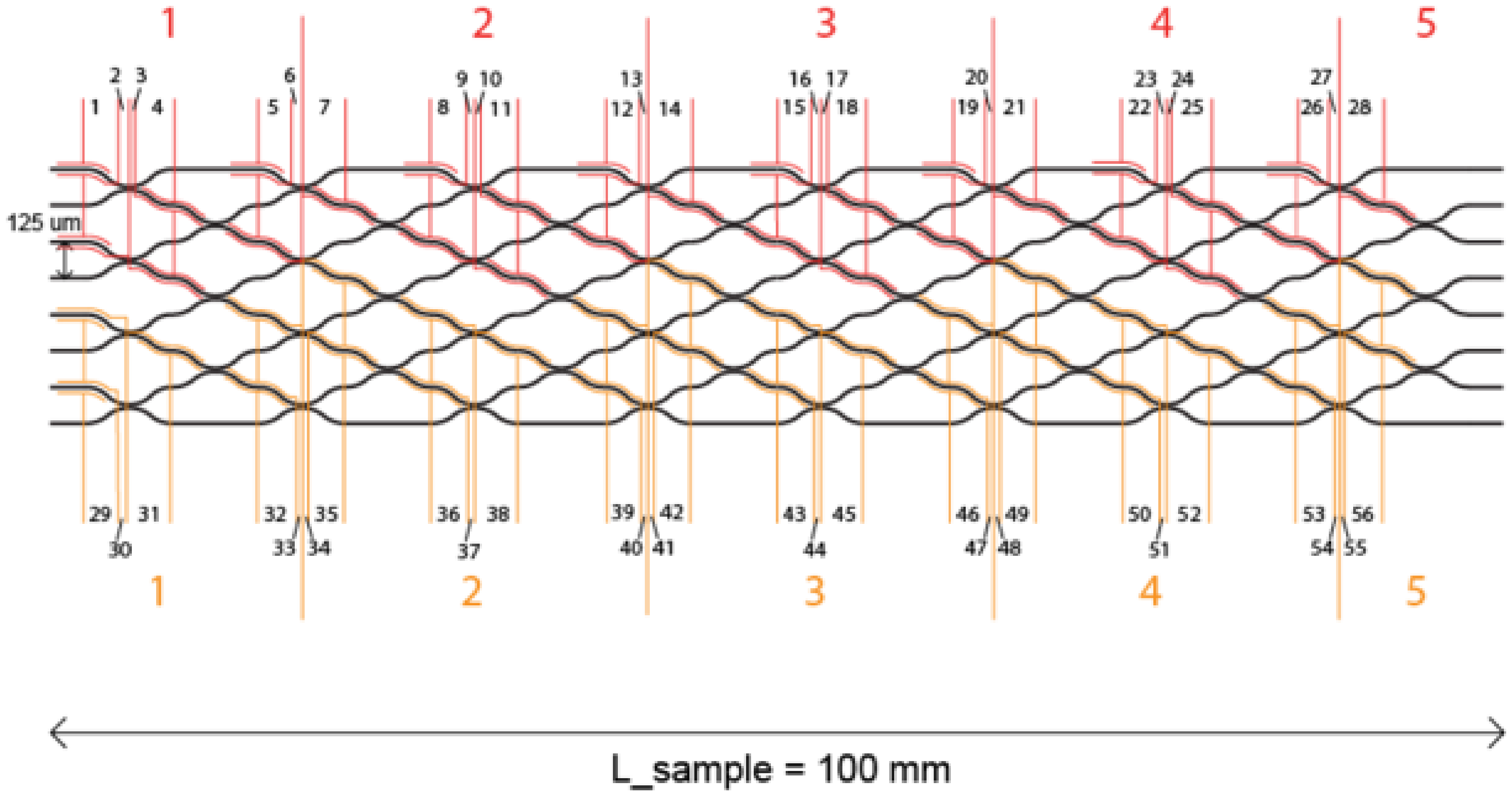
Truth table fidelity – 96%

Unitary fidelity – 98%

Current work

Error-tolerant v1
Single 10 cm chip
Electrode layout v1

d_int = 6.34 um
bs_length = 6.161 mm
R = 40 mm
56 electrodes



Summary

Femtosecond laser writing:

- Propagation loss < 1 dB/cm
- Thermooptical switching time ≈ 10 ms
- Tens of heaters on a single chip

Lithography:

- Low-loss SiN platform
- Low-loss coupling elements

OPTICAL CIRCUITS. DESIGN

Unitary design

How to design the interferometer covering the whole unitary space?

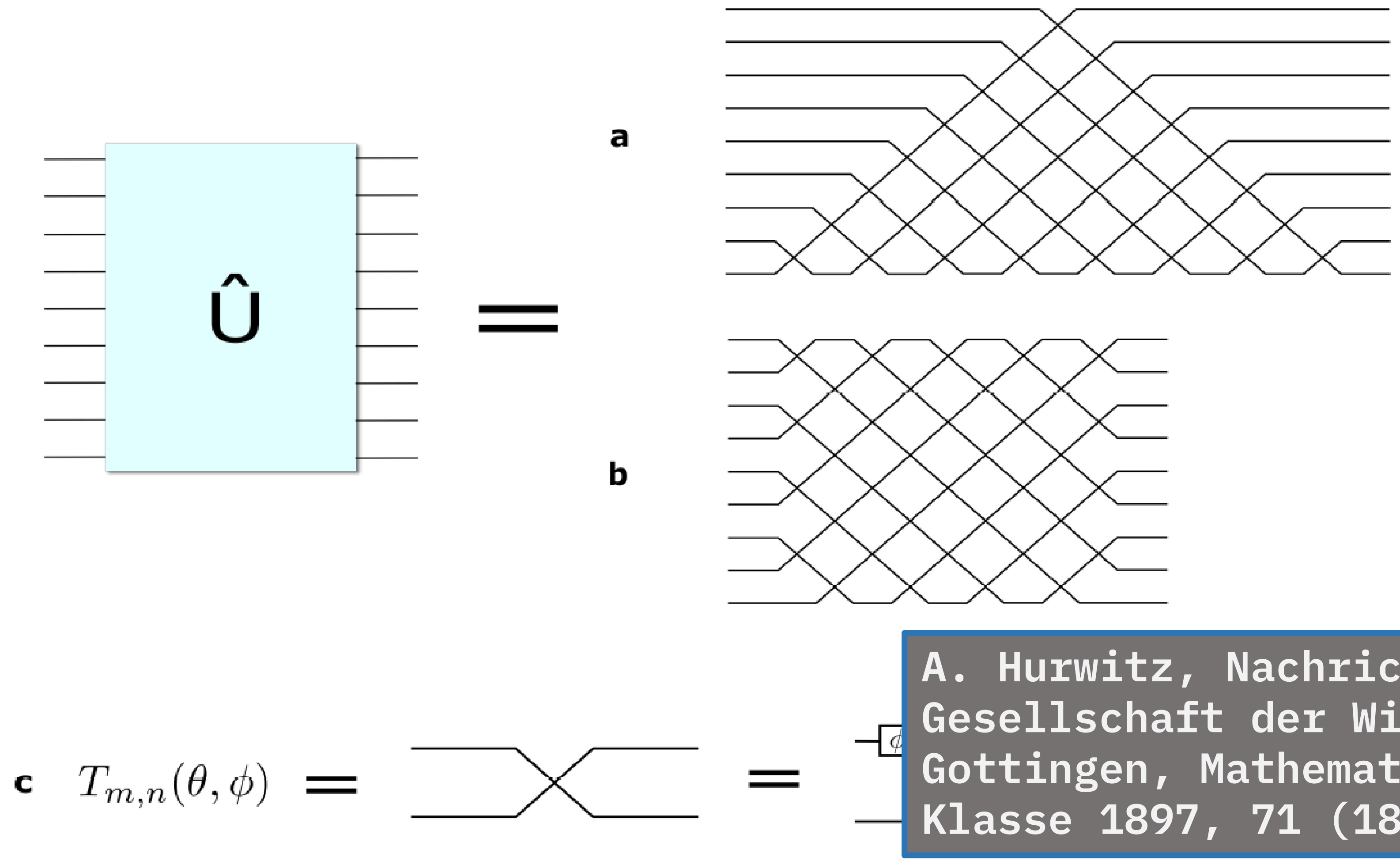
How to design the unitary for a specific gate with maximal probability of successful operation?

The goal

Find architecture of the reconfigurable interferometer covering the whole unitary space and tolerating high fabrication errors

Such architecture may find application in tasks like VQE or QAOA when no particular gate set is required but the unitary space covering must be close to complete

Map the unitary to the device



Reck scheme

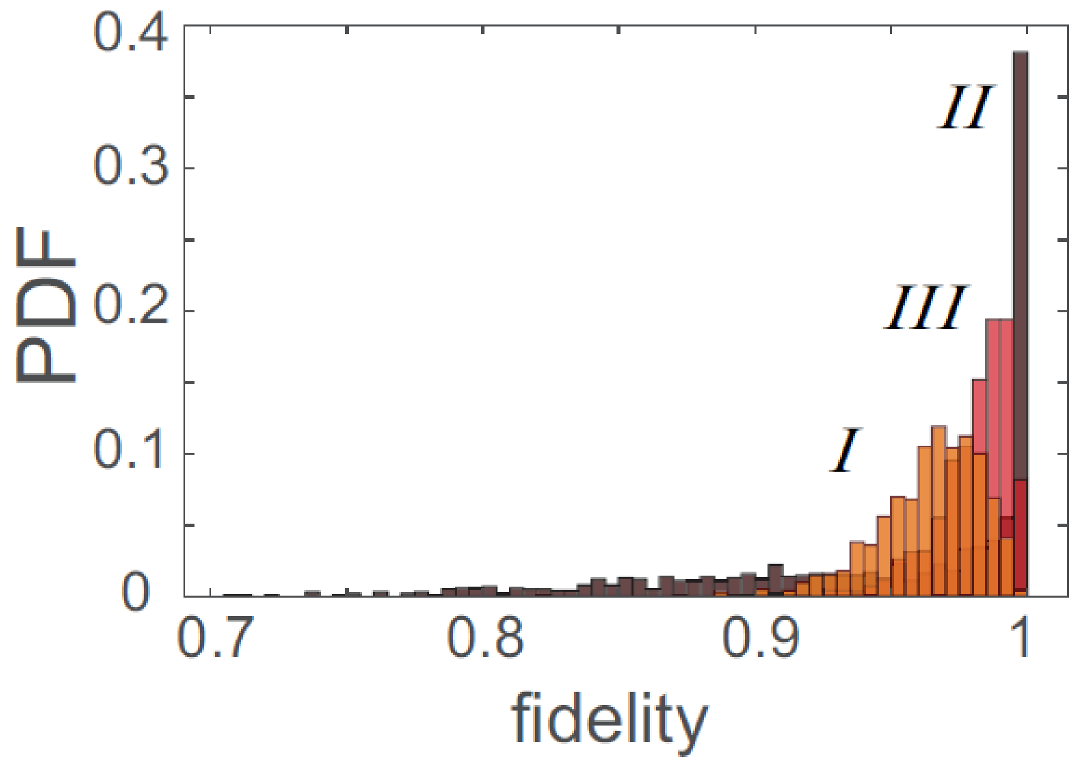
Clements scheme

A. Hurwitz, Nachrichten von der Gesellschaft der Wissenschaften zu Gottingen, Mathematisch-Physikalische Klasse 1897, 71 (1897).

Picture from W.R. Clements et al. Optica 3, 12 (2016)

Beamsplitter imbalance

Clements scheme



I – the beamsplitters are all biased with a same randomly chosen angle from the $[0, \pi/9]$ range.

II – the beamsplitters are independently biased by a random angle from the $[0, \pi/9]$ degree range.

III – the beamsplitters are independently imbalanced by a random angle from $[-\pi/9, \pi/9]$ degree range.

Optimization

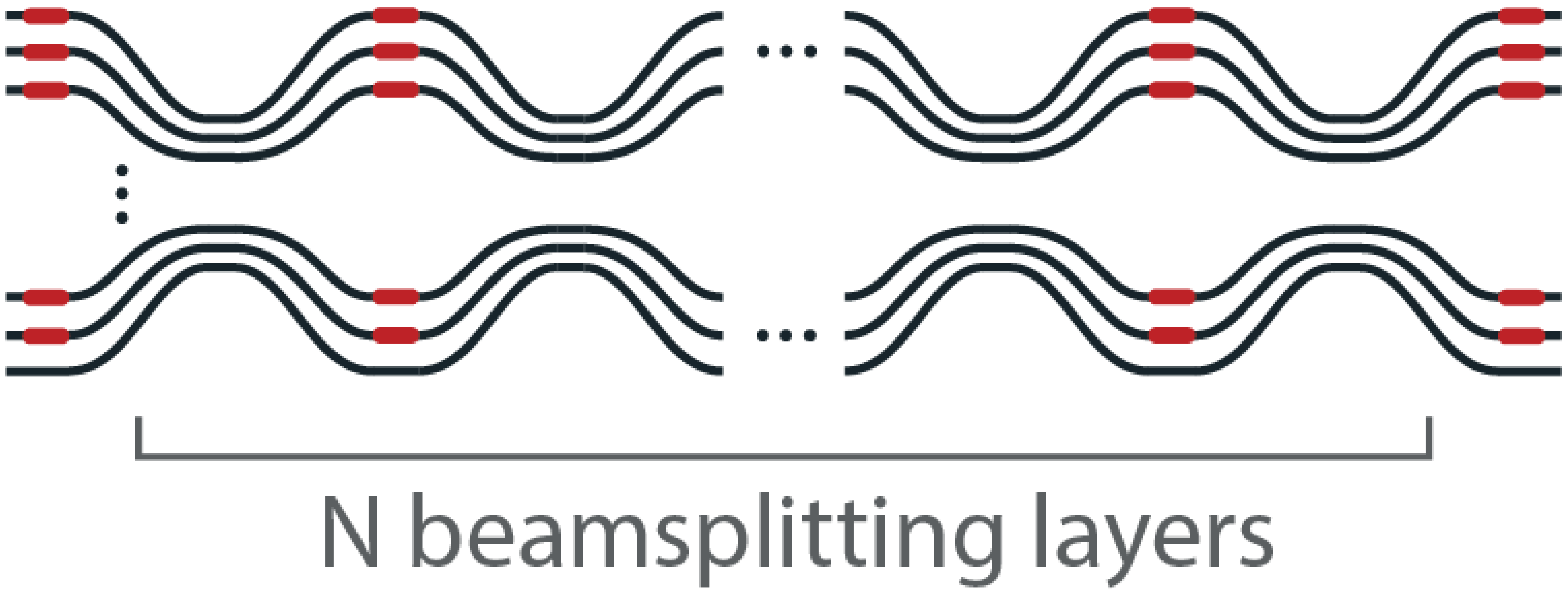
1. Haar random unitaries are generated using the QR-decomposition algorithm

2. The tested circuit parameters are fitted to match the resulting unitary of the circuit to the sampled one

3. The figure of merit $F = \frac{1}{N^2}|\mathrm{Tr}(UU_s)|^2$

4. The fidelity histogram evidences if the circuit is capable of reaching any given unitary with particular precision

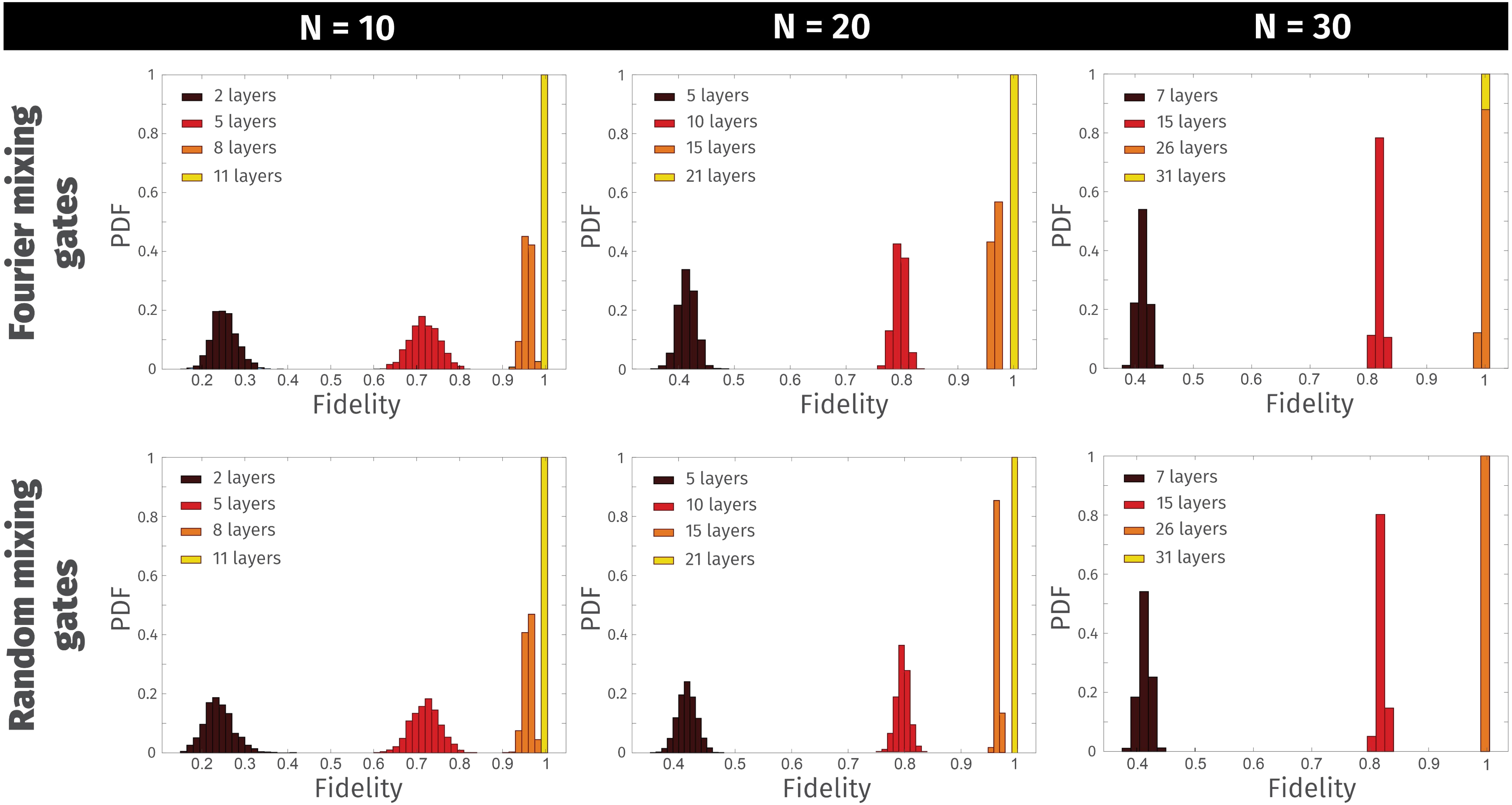
Multiport interferometer



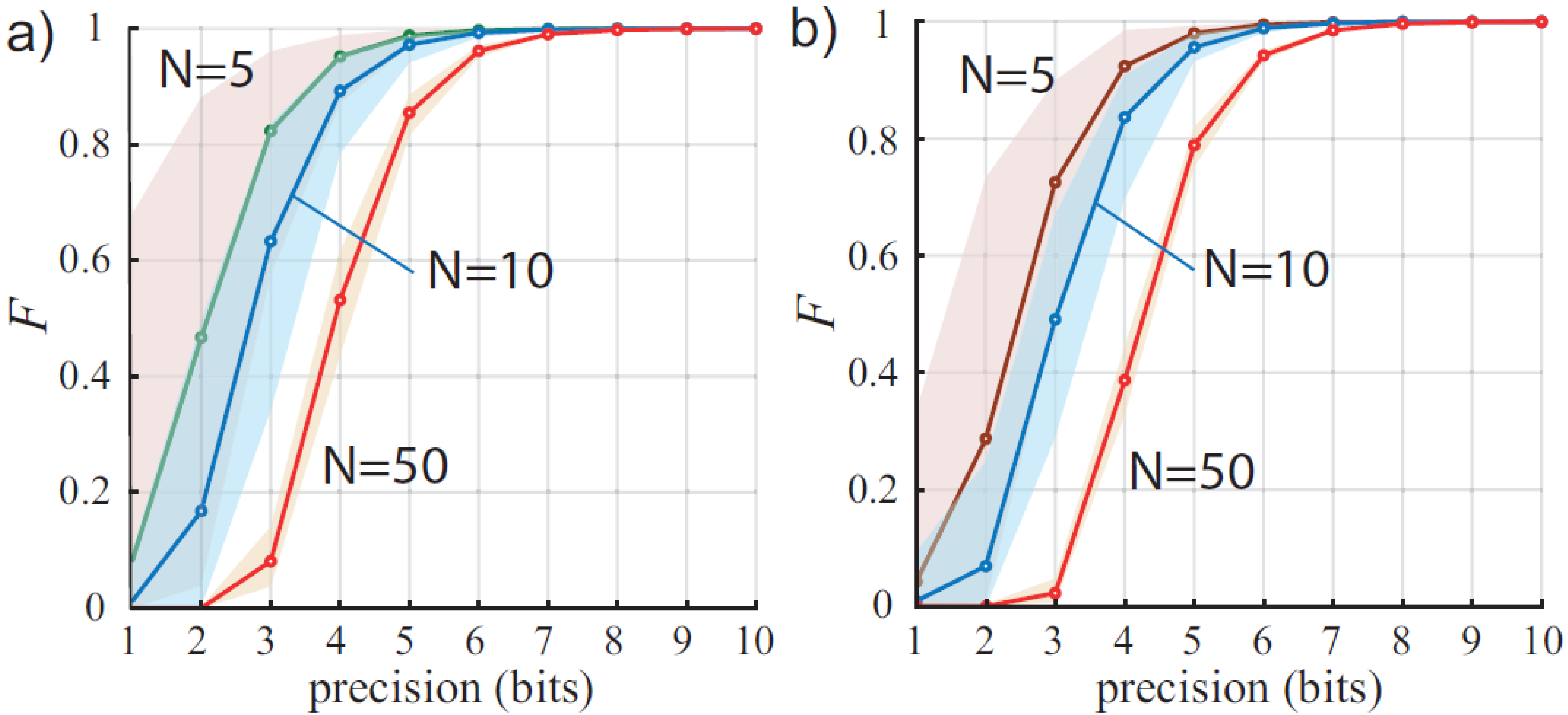
$\Lambda = \Phi^{(K+1)} V^{(K)} \Phi^{(K)} \dots V^{(1)} \Phi^{(1)}$ - **unitary matrix of the interferometer**

Lu et al. npj Quantum information 5, 24 (2019)

Numerical simulations

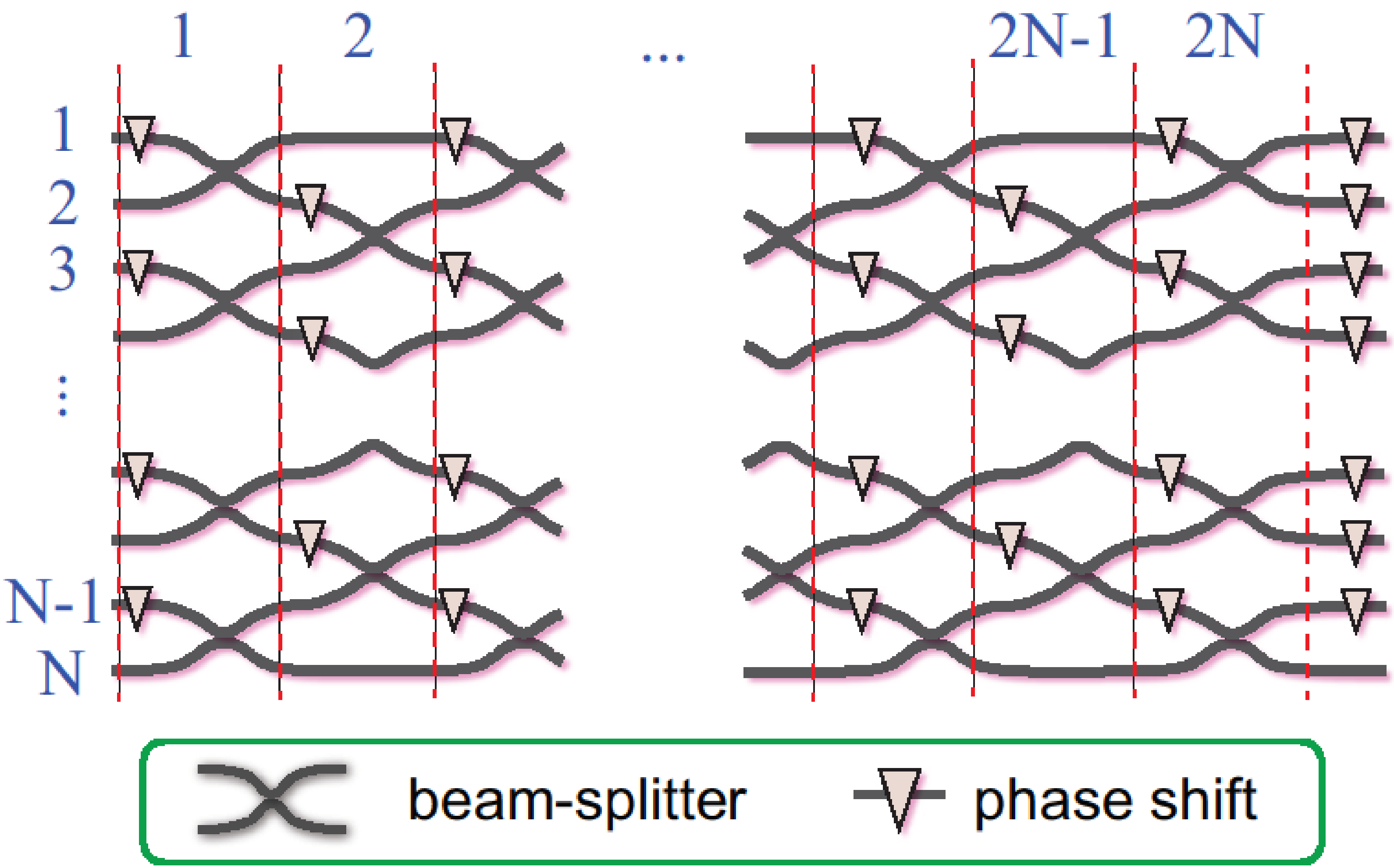


Phase precision

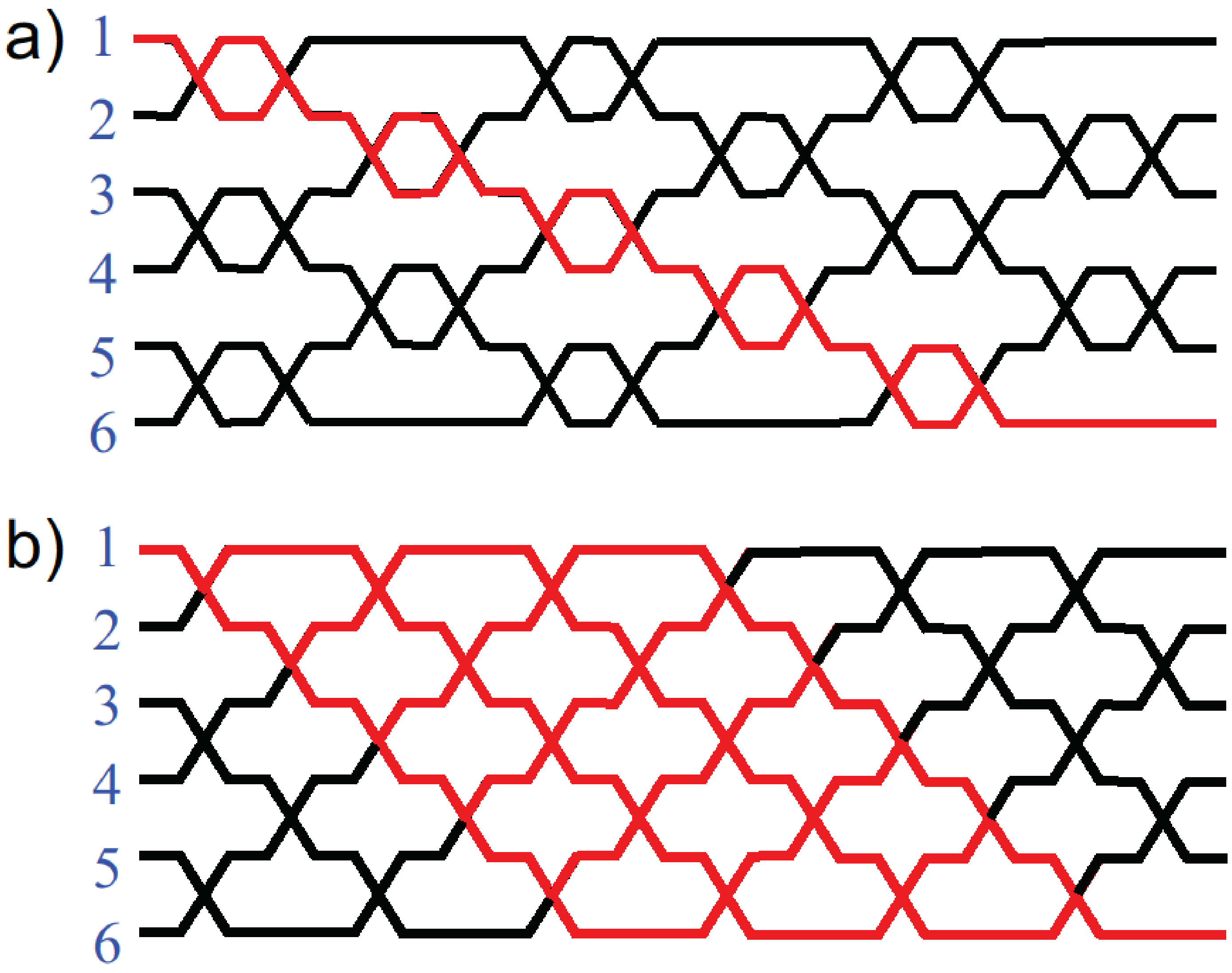


Saygin et al. Phys. Rev. Lett. 124, 010501 (2020)

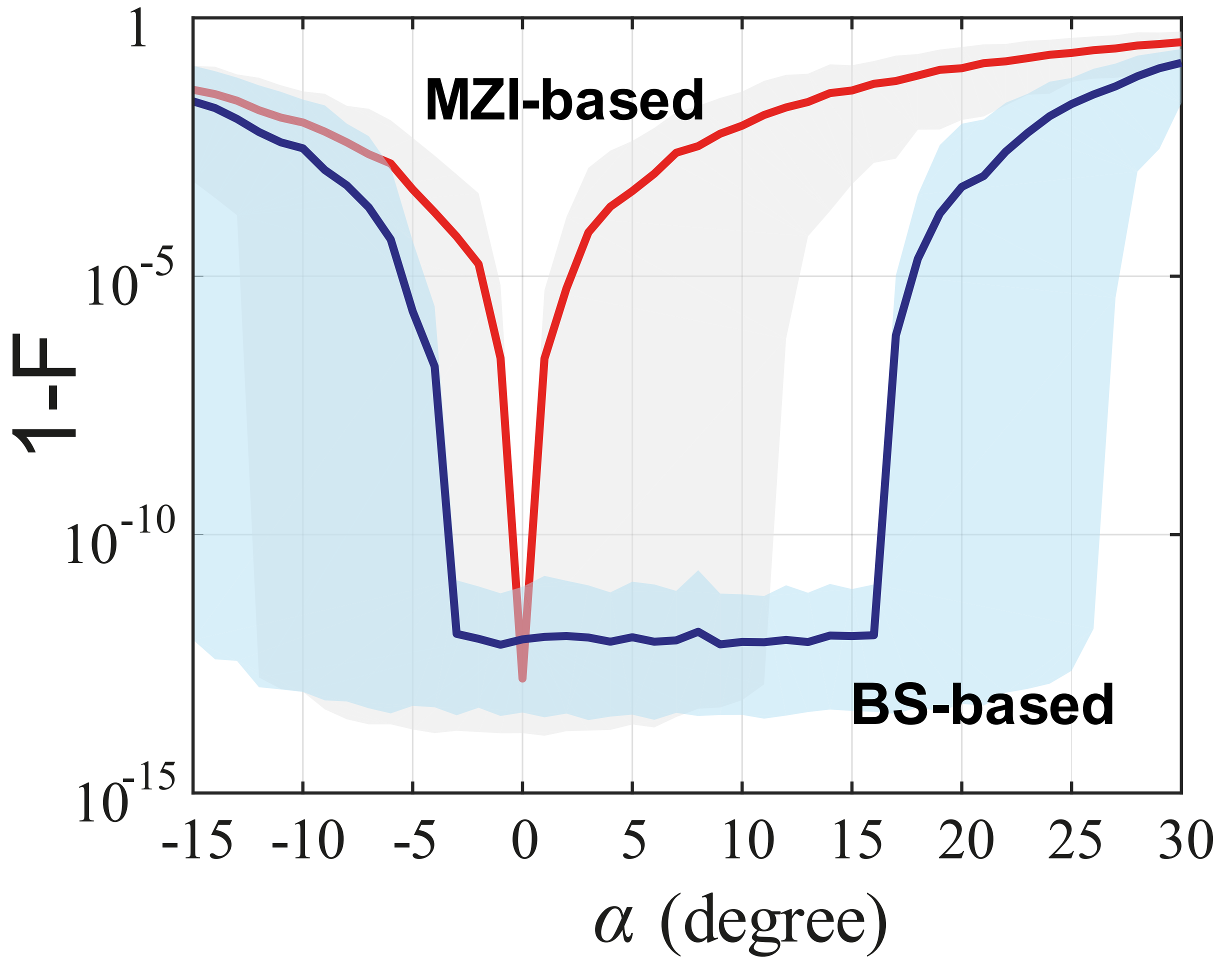
Beamsplitter mesh

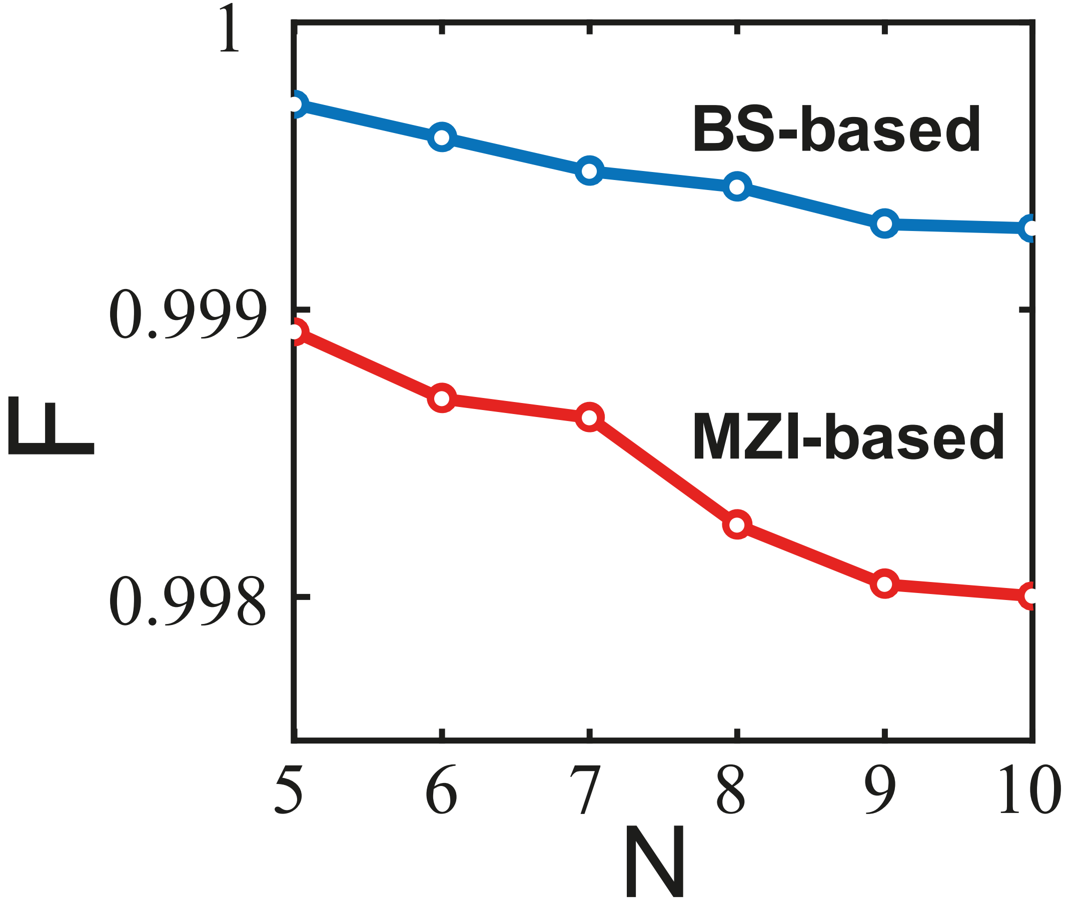


Beamsplitter mesh



Beamsplitter mesh





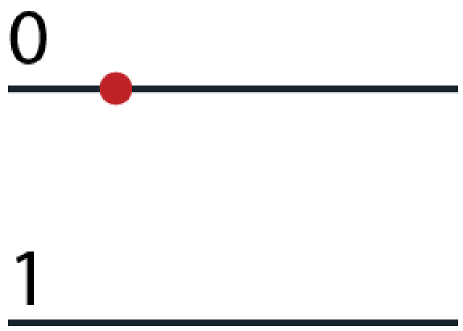
Fldzhyan et al. Optics letters 45, 9, pp. 2632-2635 (2020)

Summary

We have developed circuit architectures prone for implementing random unitaries prone to reasonably high level of fabrication imperfection

THEORY. GATE OPTIMIZATION

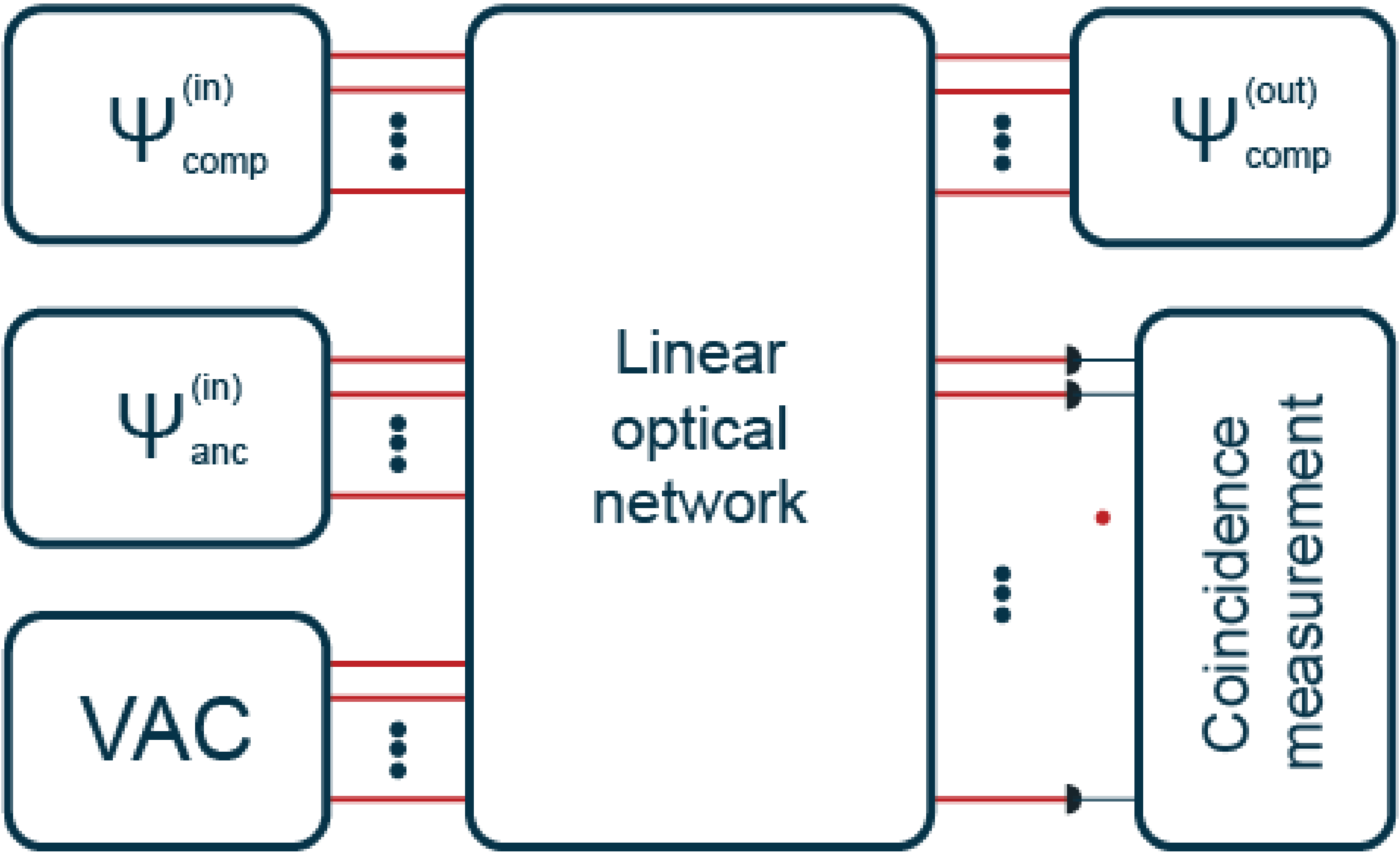
Linear optical quantum computing



Dual-rail information encoding

The gate is implemented by a specific unitary transformation Λ with a success probability $p < 1$.

Linear optical quantum computing



Fock state transformation

The matrix Λ describes the mode transformation:

$$\hat{a}_j^{out\dagger} \rightarrow \Lambda_{ij}\hat{a}_j^{in\dagger}$$

where Λ is a $M \times M$ unitary matrix, $M = M_c + M_a + M_v$.

The input state:

$$|\Psi^{in}\rangle = |n_1^c n_2^c \ldots n_{M_c}^c\rangle |n_1^a n_2^a \ldots n_{M_a}^a\rangle |vac\rangle.$$

The dimension of the system

$$dim\, H_M^N = \binom{N+M-1}{N},$$

where $N = N_c + N_a$.

Fock state transformation

The output state:

$$|\Psi^{out}\rangle = \Omega(\Lambda)|\Psi^{in}\rangle = \prod_{i=1}^{M} \frac{1}{\sqrt{n_i!}} \left(\sum_{j=1}^{M} \Lambda_{ij} \hat{a}_j^\dagger \right)^{n_i} .$$

The state of the computational subsystem after the photocounting measurement applied to $M - M_c$ ancilla and vacuum modes:

$$A(\Lambda)|\Psi^{in}\rangle = \langle k_{M_c+1}, k_{M_c+2}, \dots, k_M|\Omega(\Lambda)|\Psi^{in}\rangle,$$

$$|\Psi_c^{out}\rangle = \frac{A|\Psi^{in}\rangle}{\||A|\Psi^{in}\rangle\||}.$$

The operator A contains all the information about the gate or the state of the computational subsystem on the output.

Polynomial equations

The output state is represented by a polynomial in the creation operators:

$$|\Psi^{out}\rangle = F(\hat{a}_1^\dagger, \hat{a}_2^\dagger, \dots, \hat{a}_M^\dagger)|vac\rangle = \prod_{i=1}^{M} \frac{1}{\sqrt{n_i!}} \left(\sum_{j=1}^{M} \Lambda_{ij} \hat{a}_j^\dagger \right)^{n_i} .$$

The ancilla state is a monomial:

$$|\Psi^{anc}\rangle = |k_{M_c+1}, k_{M_c+2}, \dots, k_{M_c+M_a}\rangle = \prod_{i=M_c+1}^{M_c+M_a} \frac{1}{\sqrt{n_i!}} \hat{a}_j^{\dagger\, n_i} .$$

The heralded state $|\Psi^{her}\rangle = \langle \Psi^{anc} | \Psi^{out} \rangle$ is again a polynomial:

$$|\Psi^{out}\rangle = G(\hat{a}_1^\dagger, \hat{a}_2^\dagger, \dots, \hat{a}_{M_c}^\dagger)|vac\rangle.$$

The target state:

$$|\Psi^{tar}\rangle = Q(\hat{a}_1^\dagger, \hat{a}_2^\dagger, \dots, \hat{a}_{M_c}^\dagger)|vac\rangle$$

State generation

The problem target state generation with probability $|\alpha|^2$ is equivalent to a polynomial equation

$$G = \alpha Q,$$

which in turn is a system of polynomial equations

$$\begin{cases} poly_1(\Lambda_{11}, \Lambda_{12}, \dots, \Lambda_{NN}, \alpha) = 0, \\ \dots \\ poly_K(\Lambda_{11}, \Lambda_{12}, \dots, \Lambda_{NN}, \alpha) = 0. \end{cases}$$

Solution can be found using Groebner basis, which can be computed by the Buchberger algorithm – EXPSPACE complexity.

Optimization approach

Construct a cost function, including the success probability and fidelity and minimize it.

Target state

Example:

$$f = -\sum_{\{\Psi^{anc}\}} P(\Psi^{anc}, \Lambda) \sum_{\{\Psi^{tar}\}} |\langle \Psi^{tar} | \Psi^{anc} \rangle|^{10}$$

Two-qubit Bell states (written in the Fock basis):

$$\Psi^{tar}_{1,2} = \frac{1}{\sqrt{2}}(|1010\rangle \pm |0101\rangle)$$

$$\Psi^{tar}_{3,4} = \frac{1}{\sqrt{2}}(|1001\rangle \pm |0110\rangle)$$

$$\Psi^{tar}_{5,6} = \frac{1}{\sqrt{2}}(|1100\rangle \pm |0011\rangle)$$

Target gate

Find $\hat{A} = \alpha \hat{A}^{tar}$, where $|\alpha|^2$ - gate success probability.

Hilbert-Schmidt distance (or any other distance measure in the unitary space):

$$F(\Lambda) = \frac{\langle \hat{A} | \hat{A}^{tar} \rangle \langle \hat{A}^{tar} | \hat{A} \rangle}{\langle \hat{A} | \hat{A} \rangle \langle \hat{A}^{tar} | \hat{A}^{tar} \rangle},$$

where $\langle \hat{A} | \hat{A}^{tar} \rangle = \frac{1}{N} Tr(\hat{A}^{\dagger} \hat{A}^{tar})$.

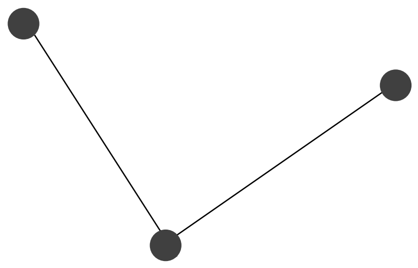
3-GHZ state generation

Three-qubit GHZ states:

$$\Psi^{tar}_{1,2,3} = \frac{1}{\sqrt{2}}(|111\rangle \pm |000\rangle)$$

Three-qubit GHZ states (written in the **Fock basis**):

$$\Psi^{tar}_{1,2,3} = \frac{1}{\sqrt{2}}(|101010\rangle \pm |010101\rangle)$$



Basic building block in ballistic QC model

The known results

6-photon 10-mode without feedforward - $P = 1/256$

6-photon 10-mode **with** feedforward - $P = 1/32$

Optimization procedure

The main optimization problem:

$$U = argmax_U \sum_{t,a} P_a(U) M_{t,a}^p$$

$$P_a(U) = \sum_m |\langle m, a|\Omega(U)|\psi_{in}\rangle|^2$$

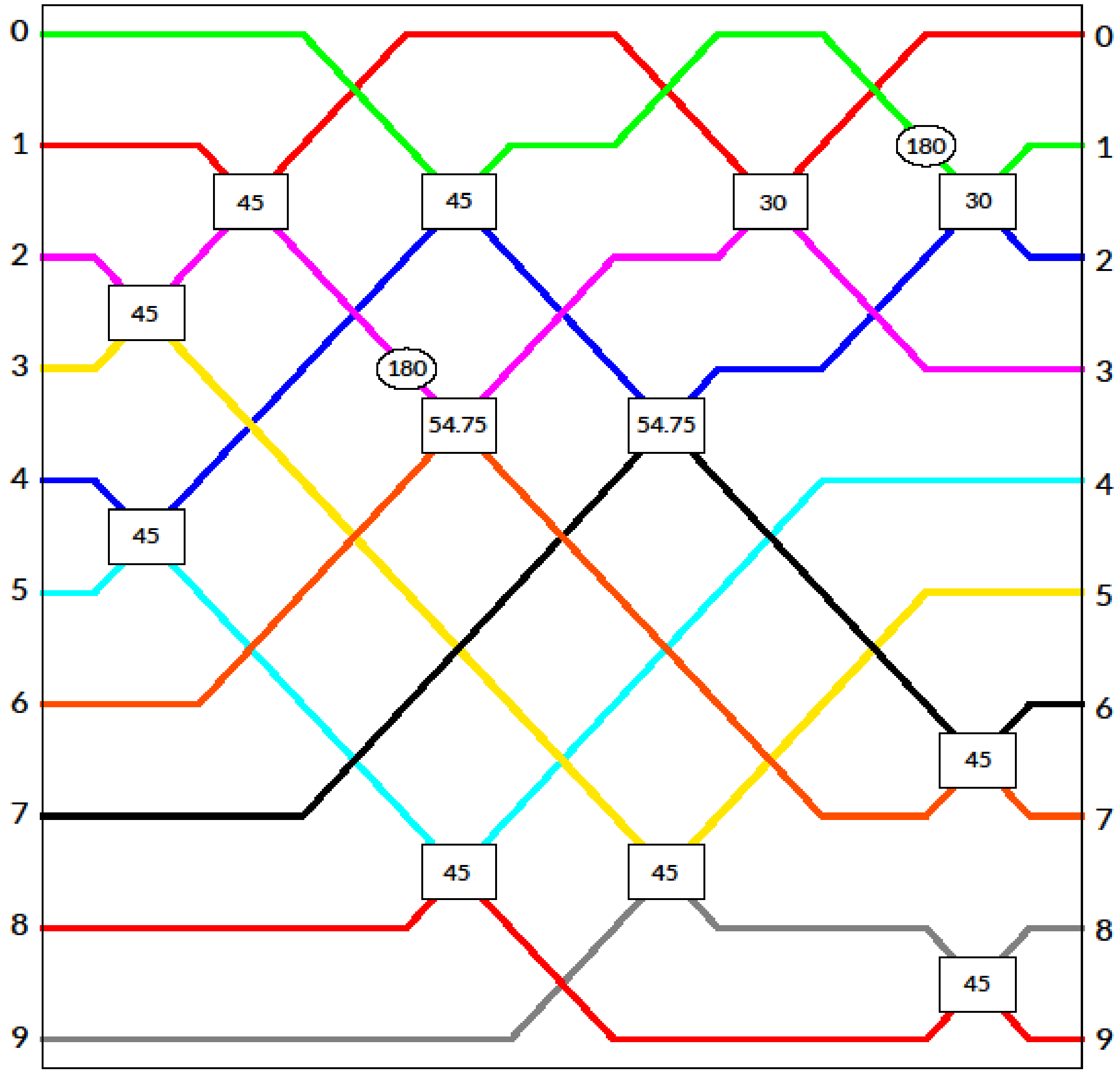
$$M_{t,a} = P_a^{-1} |\langle t, a|\Omega(U)|\psi_{in}\rangle|^2$$

The auxillary optimization problem:

$$\min S(U)$$

$$S(U) = \sum_i \{(1 - cos[4\theta_i]) + \varepsilon(1 - cos[2\varphi_i])\} + \delta \sum_i |D_i - 1|^2$$

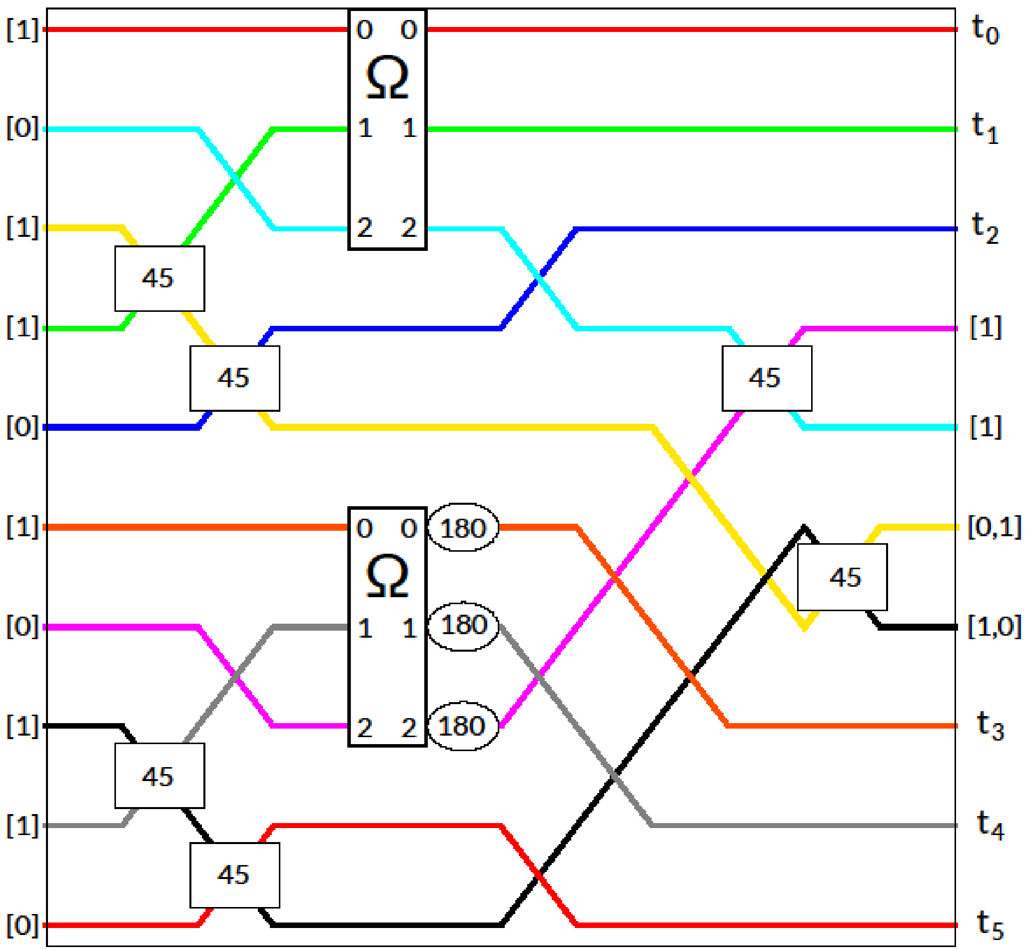
Result



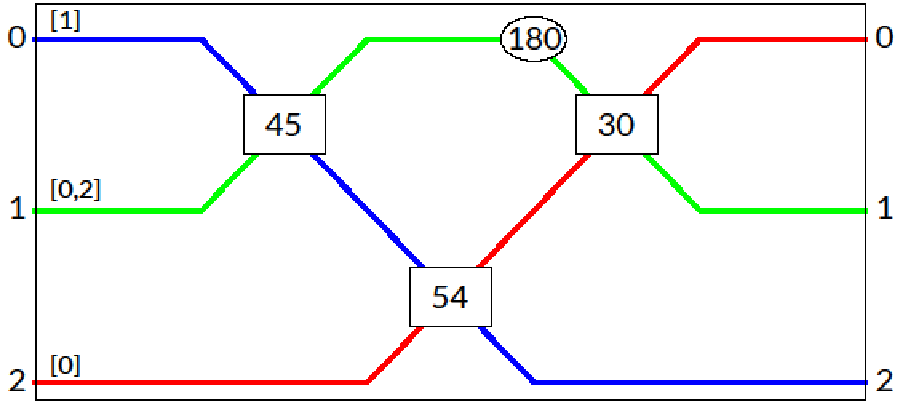
Success probability:

$$P = 1/54$$

Result



Ω block circuit:



Success probability:

$$P = 1/54$$

Gubarev et al. arXiv:2004.02691v2 (2020) Accepted to PRA

Linear optics simulation

The software package for numerical calculation of the linear optical transformation.

Github link

- Core classes are written in C++
- The code for permanent computation is optimized down to the CPU architecture (permanents up to 35x35 are easily calculated on the laptop)
- Seamless Python wrapper

Thank you for attention!