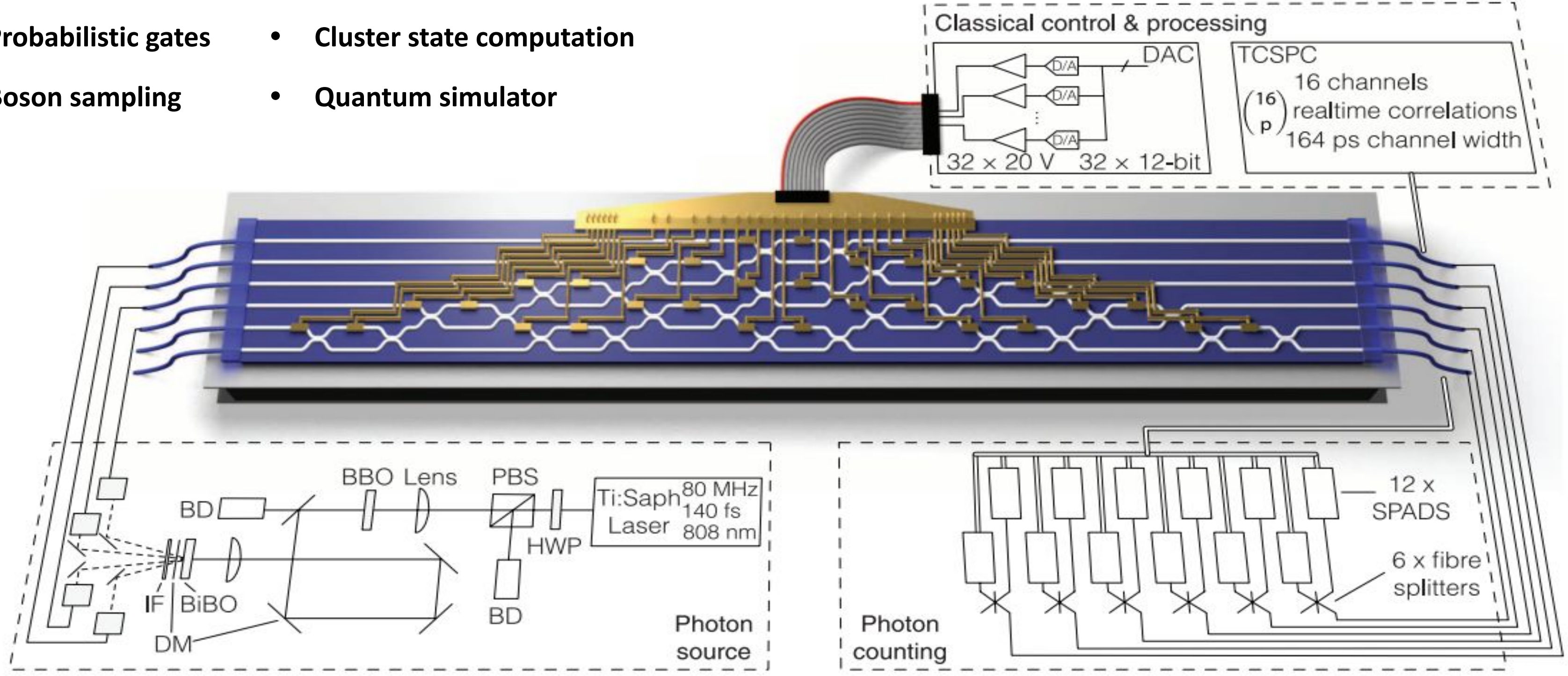
Fast Reconstruction of Programmable Integrated Interferometers

Boris Bantysh

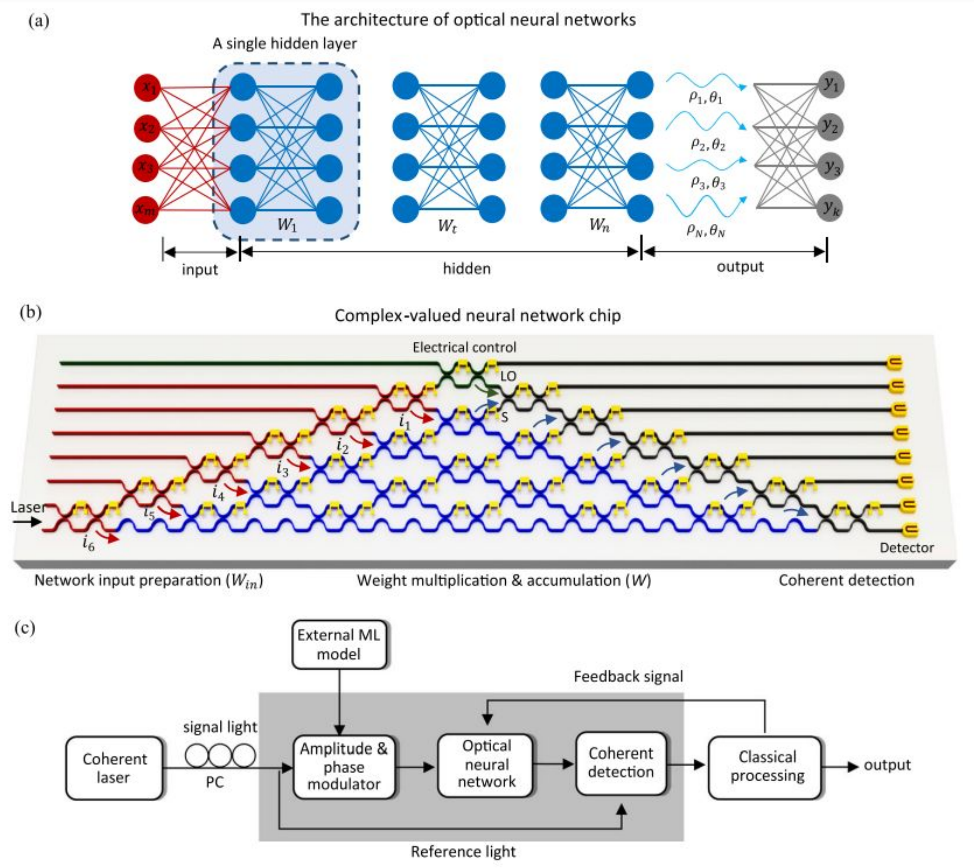
Programmable interferometers

MZI

- **Probabilistic gates**
- **Boson sampling**
- **Cluster state computation**
- **Quantum simulator**



Carolan J. et al. Science 349, 711 (2015)



Artificial neural networks with linear optical interferometers

- Solving classification problems
- Complex-valued problems
- Low energy consumption

Zhang H. et al. Nature Comm. 12, 457 (2021)

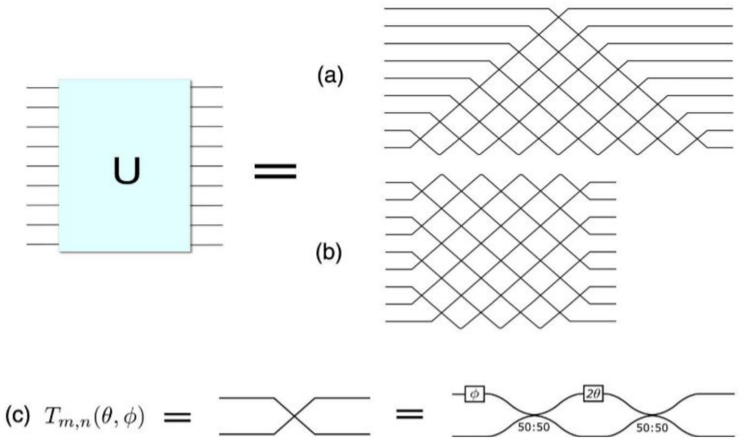
Interferometers architectures

Research Article Vol. 3, No. 12 / December 2016 / Optica 1460

optica

Optimal design for universal multiport interferometers

William R. Clements,* Peter C. Humphreys, Benjamin J. Metcalf, W. Steven Kolthammer, and Ian A. Walmsley

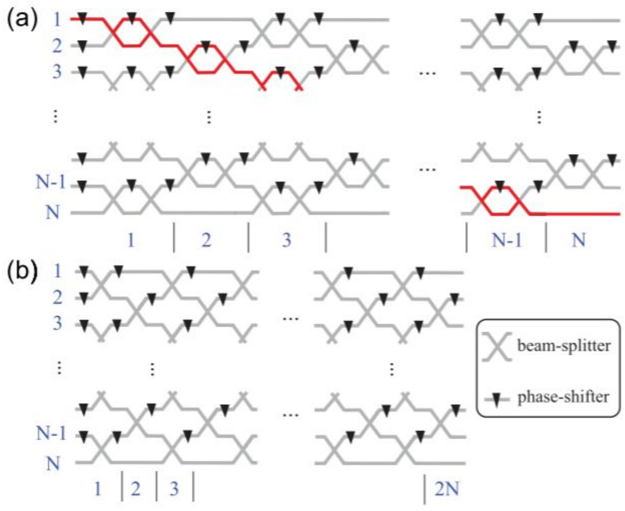


2632 Vol. 45, No. 9 / 1 May 2020 / Optics Letters Letter

Optics Letters

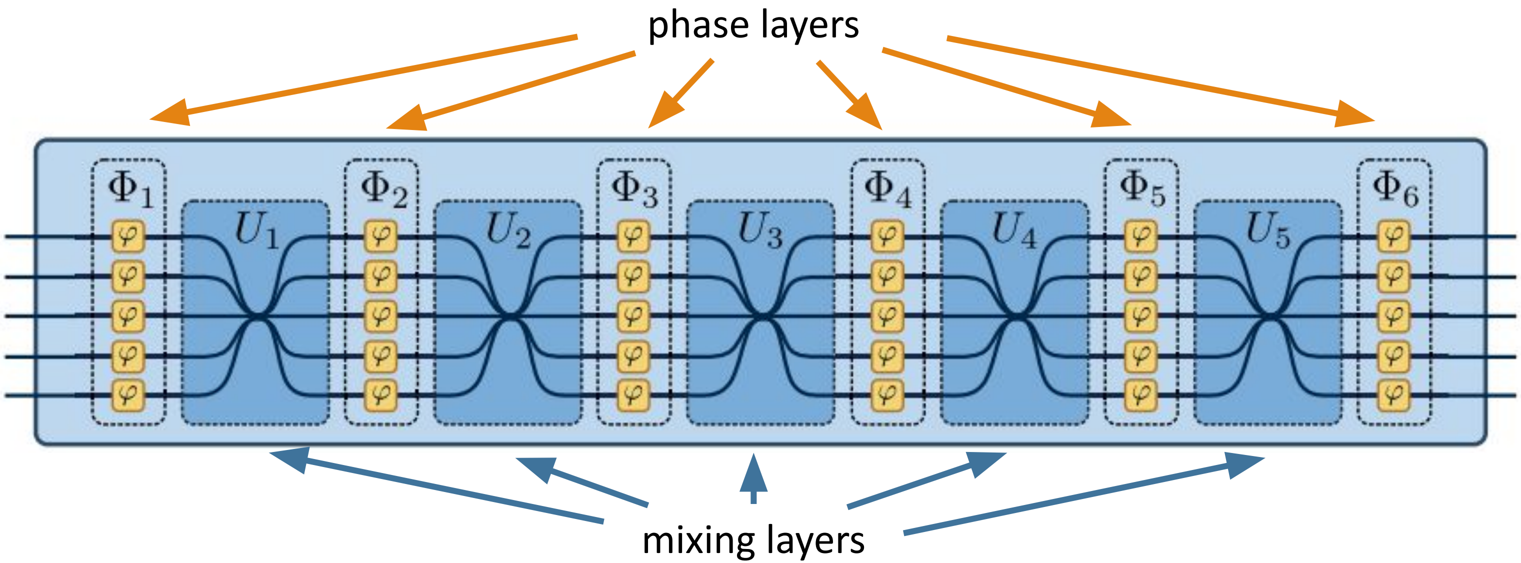
Optimal design of error-tolerant reprogrammable multiport interferometers

S. A. Fldzhyan, M. Yu. Saygin,* and S. P. Kulik



Robust Architecture for Programmable Universal Unitaries

M. Yu. Saygin, I. V. Kondratyev, I. V. Dyakonov, S. A. Mironov, S. S. Straupe, and S. P. Kulik
Phys. Rev. Lett. **124**, 010501 – Published 2 January 2020



$$V = \Phi_{K+1} U_K \Phi_K \dots U_2 \Phi_2 U_1 \Phi_1$$

Programmable interferometer characterization

Research Article Vol. 5, No. 7 / July 2018 / Optica

optica

Training of photonic neural networks through *in situ* backpropagation and gradient measuremen

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[2]Ginzton Laboratory and Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA
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Matrix Optimization on Universal Unitary Photonic Devices

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(Received 7 August 2018; revised manuscript received 18 April 2019; published 19 June 2019)

Conference on Lasers and Electro-Optics OSA Technical Digest (Optica Publishing Group, 2020), paper SM1E.5 • https://doi.org/10.1364/CLEO_

CLEO

Parallel Fault-Tolerant Programming and Optimization of Photonic Neural Network

Sunil Pai, Ian A. D. Williamson, Momchil Minkov, Tyler W. Hughes, Olav Solgaard, Shanhui Fan, and David A. B. Miller

Research Article Vol. 29, No. 23 / 8 Nov 2021 / Optics Express 38429

Optics EXPRESS

Architecture agnostic algorithm for reconfigurable optical interferometer programming

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Research Article Vol. 31, No. 10 / 8 May 2023 / Optics Express 16729

Optics EXPRESS

Fast reconstruction of programmable integrated interferometers

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[2] Russian Quantum Center, Skolkovo, Moscow 143025, Russia
[*] k.g.katamadze@gmail.com

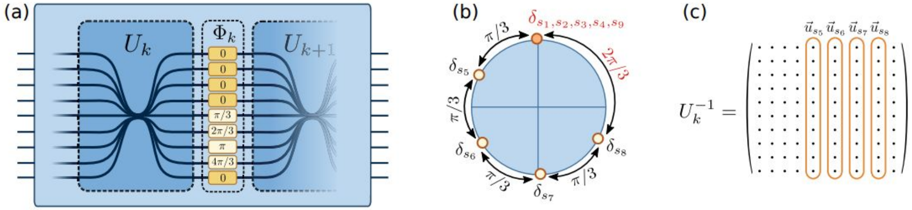


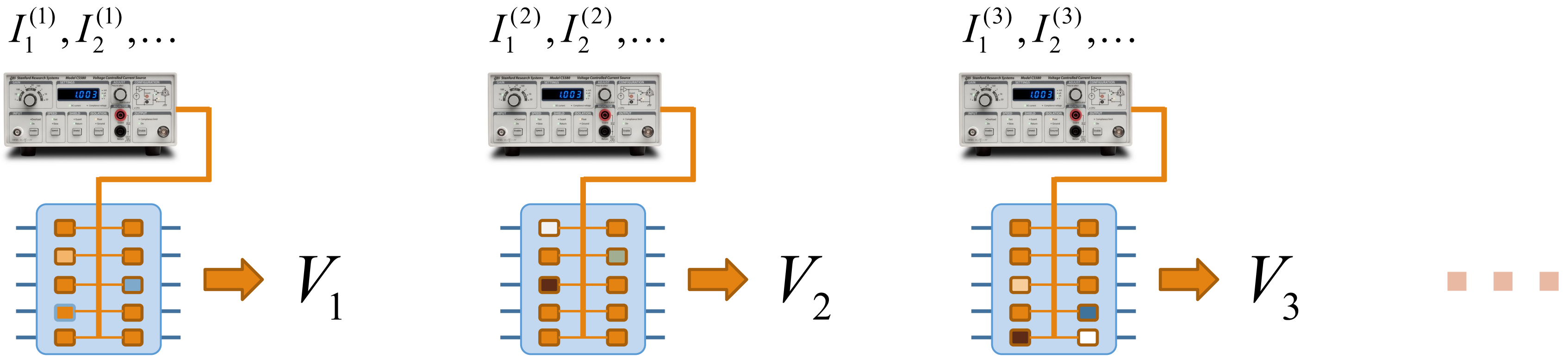
Fig. 4. An example of a partial reconstruction of the inverse matrix of the k-th mixing layer. The dimension of the interferometer is $N = 9$. $M = 4$ matrix columns from 5 to 8 are estimated. (a) The k-th phase layer configuration. (b) The phases of matrix A_k eigenvalues are sorted on the unit circle in ascending order. The first element is considered to be the one that is separated from the previous one by the largest distance. The first $N - M = 5$ elements correspond to eigenvectors with indices $n \notin C$. The remaining $M = 4$ elements are eigenvectors with indices $n \in C$. (c) The corresponding eigenvectors are set to be the columns of the matrix U_k^{-1}.

Algorithm 1. Mixing layers reconstruction

Measure V_0 (all phase layers are disabled)
$V_T \leftarrow I$ ▹ The product of all currently estimated U_k
for $k = 1, \dots, K-1$ **do**
  $U_k^{(\mathrm{inv})} \leftarrow I$ ▹ Initial estimation
  $j \leftarrow 0$ ▹ Current number of estimated columns
  while $j < N$ **do**
    $M' = \min(M, N - j)$
    if $M' = N$ **then** ▹ All columns of U_k^{-1} are estimated at once
      $\varphi_n \leftarrow \frac{2\pi(n-1)}{N\ 1}$ $(n = 1, \dots, N)$
    else ▹ Only M' columns of U_k^{-1} are estimated
      $\varphi_n \leftarrow 0$ $(n = 1, \dots, N)$
      $\varphi_{j\ m} \leftarrow \frac{2\pi m}{M'\ 2}$ $(m = 1, \dots, M')$
    end if
    Measure V_k (phases of $(k\ \ 1)$-th phase layer are φ_n)
    $A_k \leftarrow V_T V_0^{-1} V_k V_T^{-1}$
    Solve $A_k \vec{u}_q = r_q e^{i\delta_q} \vec{u}_q$ for $\vec{u}_q, r_q \geq 0, \delta_q \in [0, 2\pi)$ $(q = 1, \dots, N)$
    Find sorting indices S using (15)
    $[U_k^{(\mathrm{inv})}]_{n,j\ m} \leftarrow [\vec{u}_{s_{N-M'\ m}}]_n$ $(m = 1, \dots, M')$ ▹ Update M' columns of U_k^{-1} to match sorted eigenvectors of A_k
    $j \leftarrow j\ \ M'$
  end while
  $U_k \leftarrow [U_k^{(\mathrm{inv})}]^{-1}$
  if Using unitary model **then**
    $U_k \leftarrow \mathrm{proj}[U_k]$ using (17)
  end if
  $V_T \leftarrow U_k V_T$
end for
$U_K \leftarrow V_0 V_T^{-1}$

PQCLab/ILOptics

Data for reconstruction



Direct characterization of linear and quadratically nonlinear optical systems

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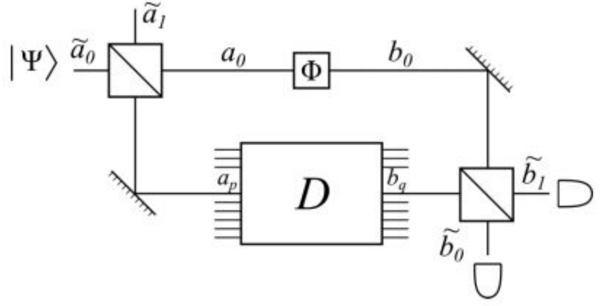
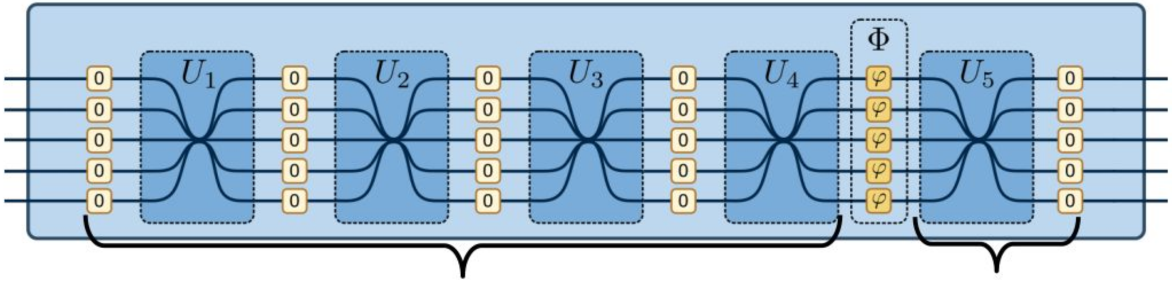
(Received 12 July 2018; published 21 November 2018)



Algorithm



$$B = U_4 U_3 U_2 U_1 \qquad U_5$$

$$\Phi = \text{diag}[\exp(i\varphi_n)]$$

$$V_0 = U_5 B \qquad V_5 = U_5 \Phi B$$

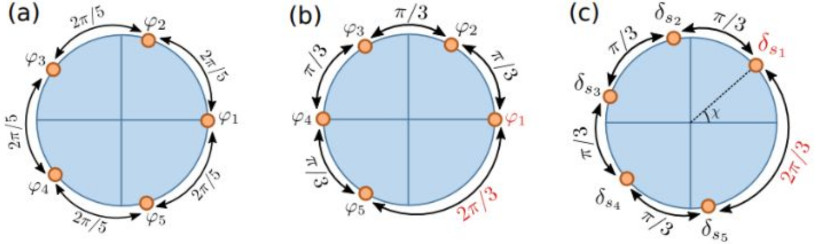
$$A = V_5 V_0^{-1} = U_5 \Phi U_5^{-1}$$

find U_5 from A by diagonalization

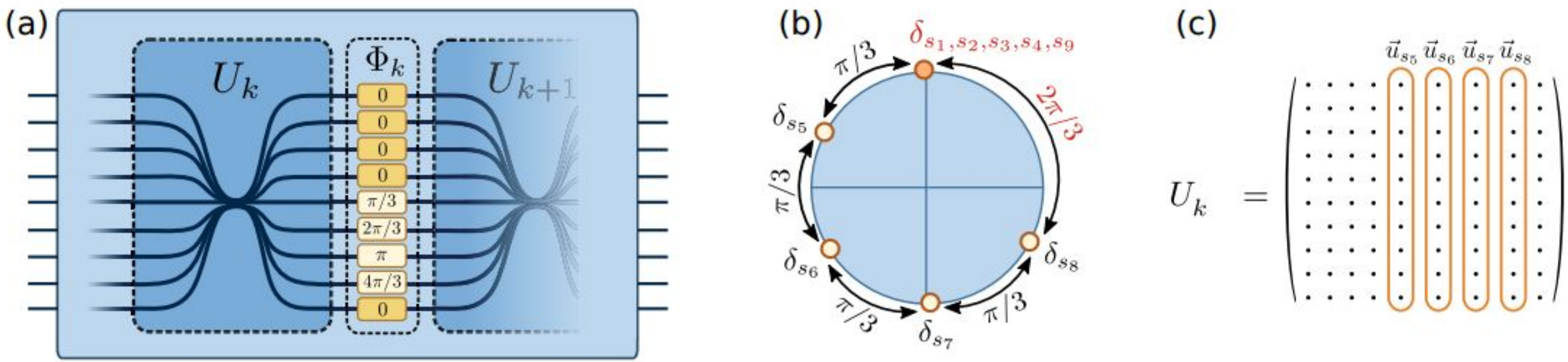
$$A \cdot \vec{u}_q = e^{i\varphi_n} \cdot \vec{u}_q, \quad q = 1, \ldots, N$$

continue from right to left and find matrices of all mixing layers

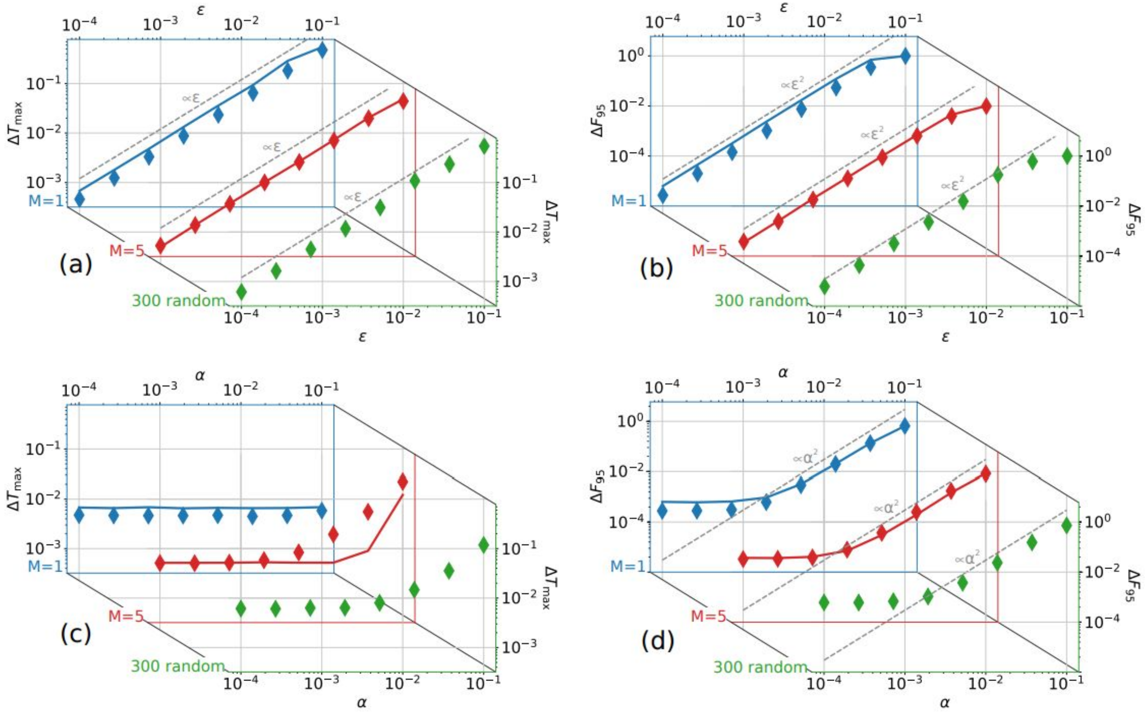
Choose phases wisely $\{\varphi_n + \chi\} \neq \{\varphi_n\}, \quad \forall \chi$



Robustness to phase control errors

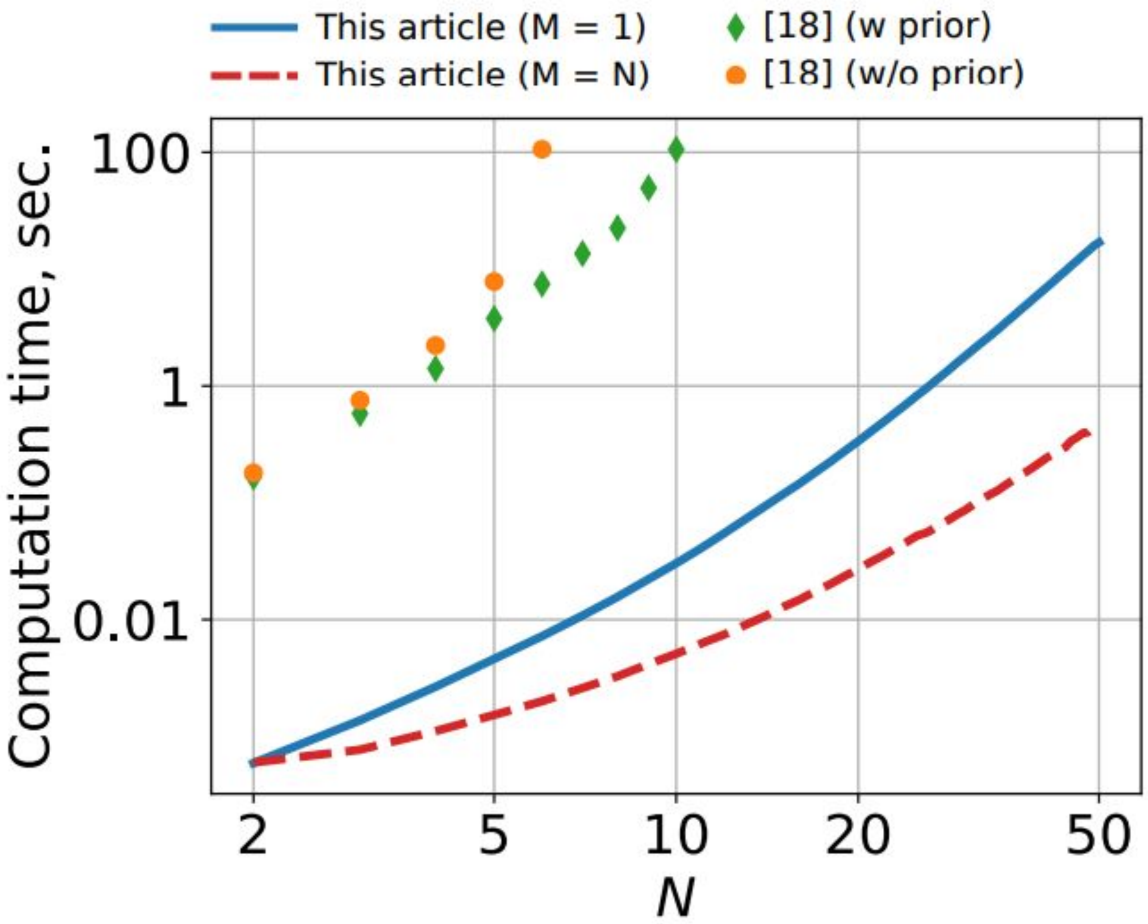


Simulation results

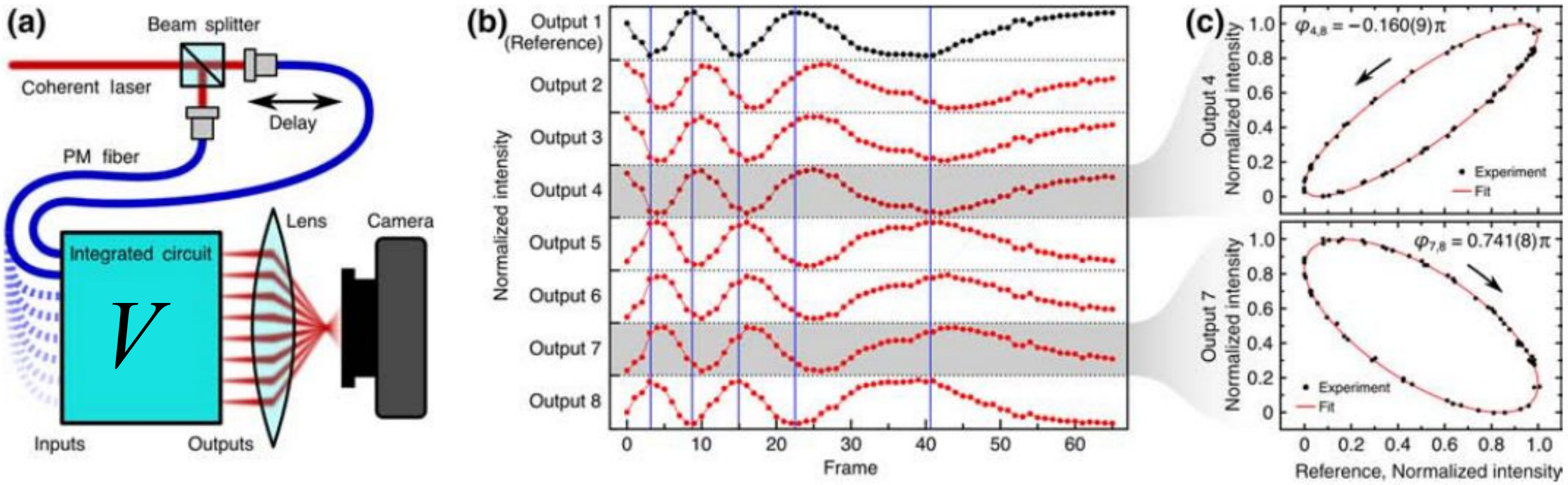


Accuracy versus full matrices measurement error

Accuracy versus phases control error


This article (M = 1)
This article (M = N)
[18] (w prior)
[18] (w/o prior)
Computation time, sec.
100
1
0.01
2
5
10
20
50
N

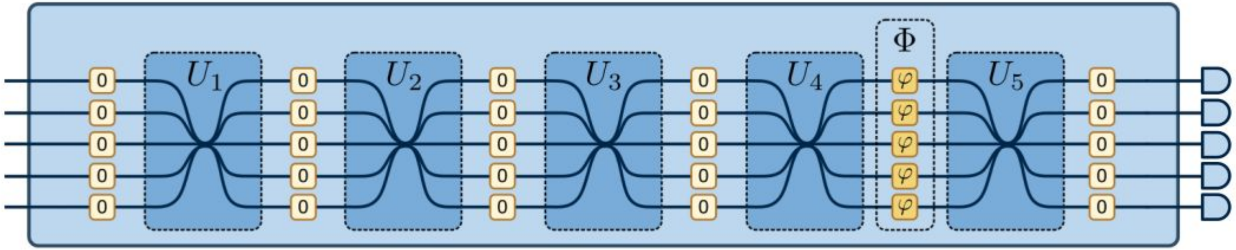
Issue 1: Intensity-only measurements



V and $V' = \mathrm{diag}[\exp(i\delta_n)]V$ give the same output intensities

Heilmann R. et al. Sci. Bull. 60, 96 (2015)

Conjugate phases trick



$$V_0 = D_0 U_5 B$$
$$V_5 = D_5 U_5 \Phi B$$
$$V_5' = D_5' U_5 \Phi^* B$$

↑ unknown diagonal phase matrices

⇒

$$V_0 = \tilde{U}_5 B$$
$$V_5 = \tilde{D}_5 \tilde{U}_5 \Phi B$$
$$V_5' = \tilde{D}_5' \tilde{U}_5 \Phi^* B$$

$$\tilde{D}_5 = D_5 D_0^*$$
$$\tilde{D}_5' = D_5' D_0^*$$

⇒

$$X = V_5 V_0^{-1} = \tilde{D}_5 \tilde{U}_5 \Phi \tilde{U}_5^{-1}$$
$$Y = V_0 [V_5']^{-1} = \tilde{U}_5 \Phi \tilde{U}_5^{-1} [\tilde{D}_5']^*$$

⇒

$$X = \tilde{D}_5 Y \tilde{D}_5'$$

⇓

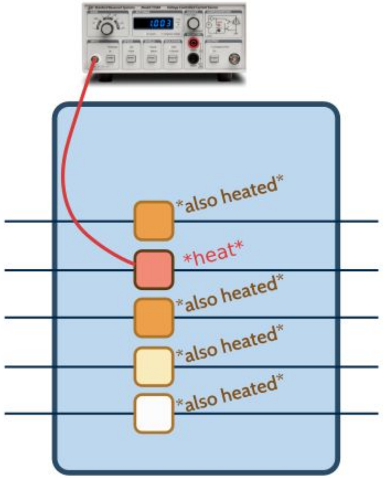
$$\delta_n = \arg x_{n0} - \arg y_{n0} + const$$

⇓

$$A = \tilde{D}_5^* V_5 V_0^{-1} = \tilde{U}_5 \Phi \tilde{U}_5^{-1}$$

Bantysh B.I. et al. Laser Phys. Lett. 21, 015203 (2023)

Issue 2: Controls cross-talk



No cross-talk: $$\varphi_k = A_k I_k^2 + B_k$$

Linear cross-talk: $$\varphi_k = \sum_i A_{ki} I_i^2 + B_k$$

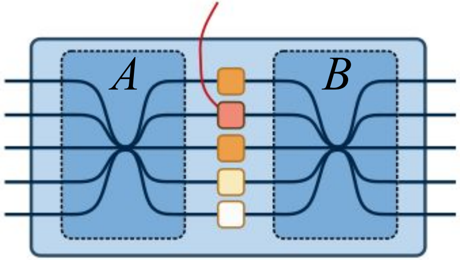
A_{ki} → cross-talk matrix

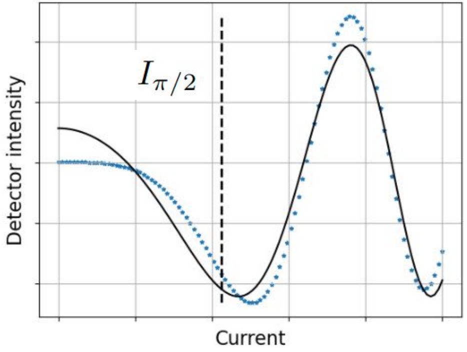
Cannot perform conjugate phases trick

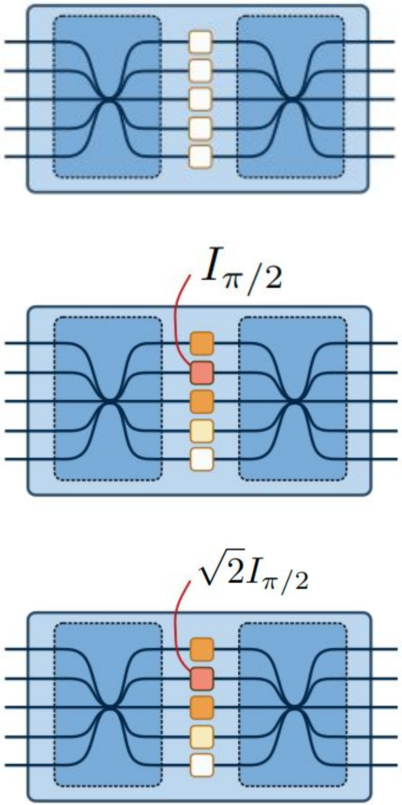
Cross-talk compensation: $$I_i = \left(\sum_k \left[A^{-1}\right]_{ik} \Delta\varphi_k \right)^{1/2}$$

Square phases trick

scan through currents and approximate pi/2-current







$$V_0 = BA$$

$$V_1 = D_1 B \Phi A$$

$$V_2 = D_2 B \Phi^2 A$$

In analogy to conjugate phases one finds D1 and D2

$$X = B \Phi B^{-1}$$

* The largest eigenvalues phase corresponds to the second **column of *B***

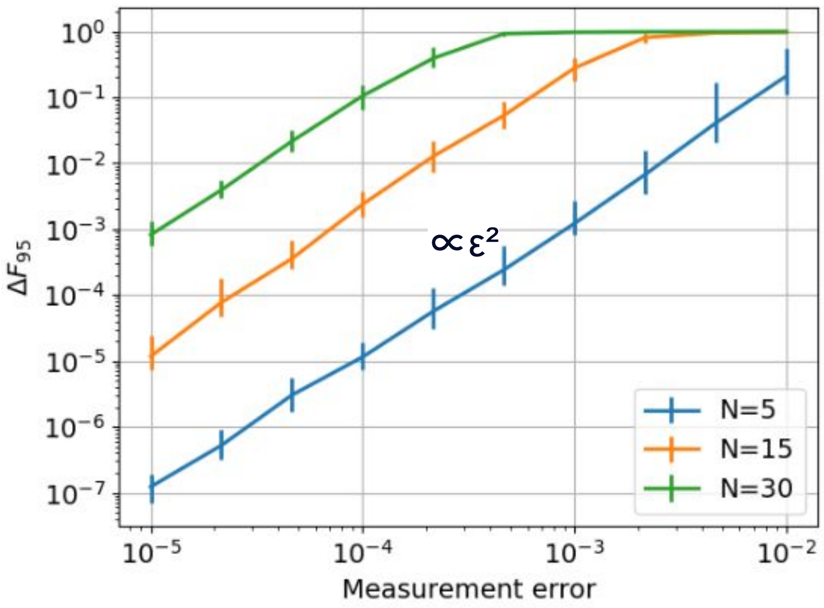
* Others eigenvalues phases give **cross-talk matrix coefficients**

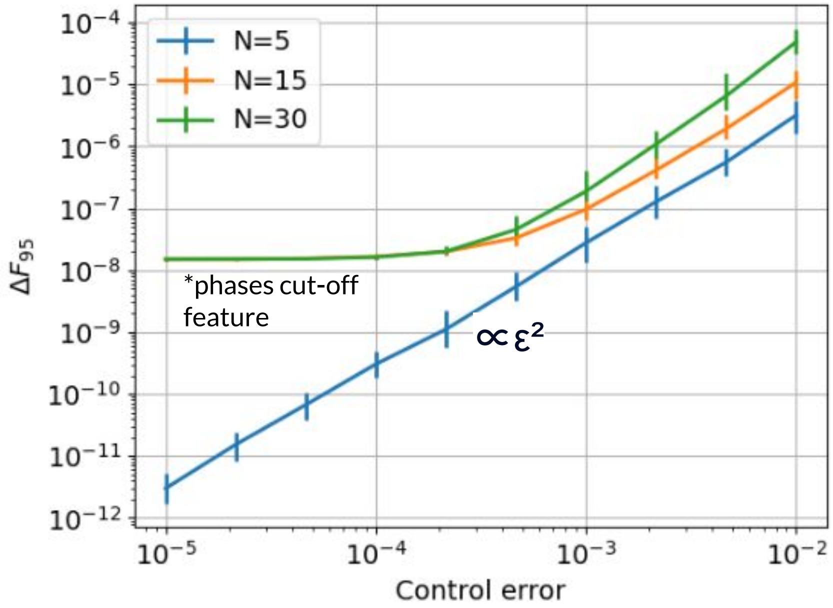
Simulation results

➔ random mixing layers

➔ random k-diagonal cross-talk matrix

95th quantile of transfer matrix prediction infidelity





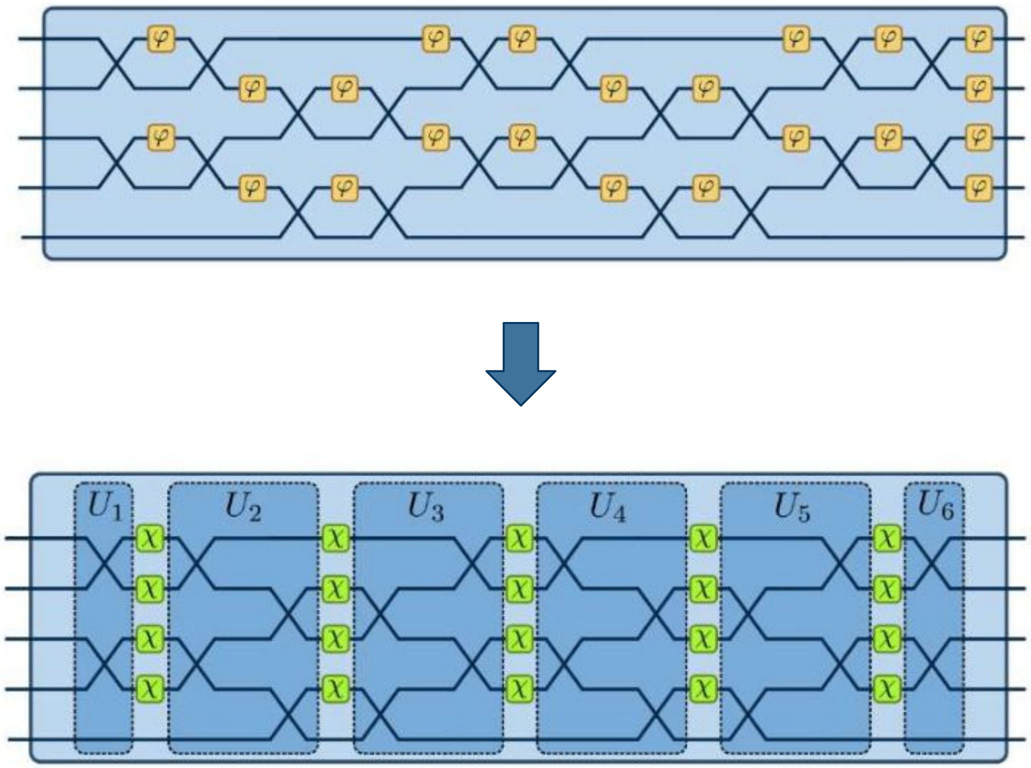
Conclusions

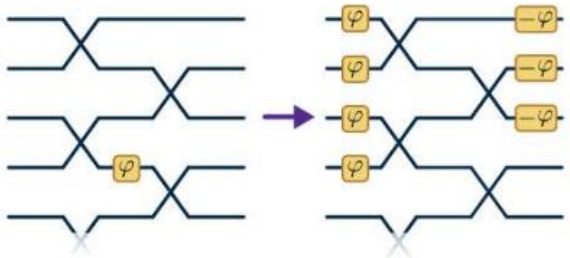
- The algorithm extracts both mixing layer elements and phase layer cross-talk parameters
- The algorithm does not use numerical optimization
- Requires measuring the transfer matrix for 2xNxK+1 different probe currents
- Waiting for experiment data
- TODO: check and improve for non-linear model

Thank you

For your attention!

Clements' architecture





We can use the same approach with slightly modified controls