Self-configuring photonics – circuits, architectures, topologies and algorithms

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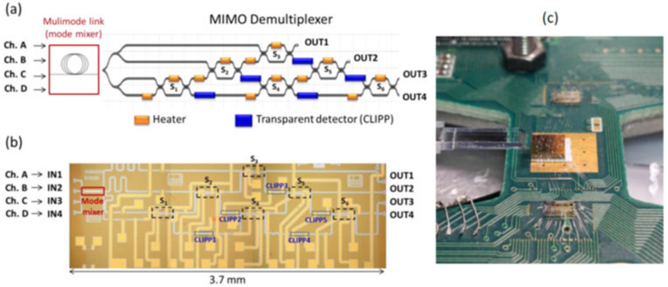
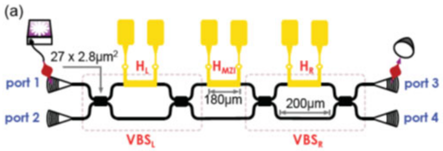
Introduction

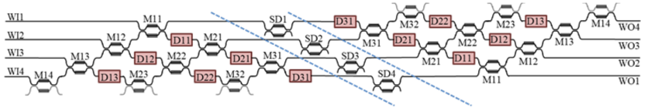
- In recent years, we have discovered architectures and algorithms that
  - allow control and programming of complex photonic circuits
  - automatically self-configure and self-stabilize
    - including adapting to problems that change in time
- with many potential applications, e.g.,
  - communications
  - information processing
  - sensing



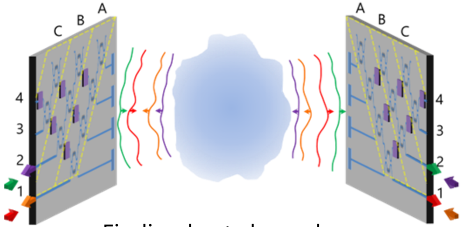
Automatic separation of mixed modes



Perfect optics from imperfect components



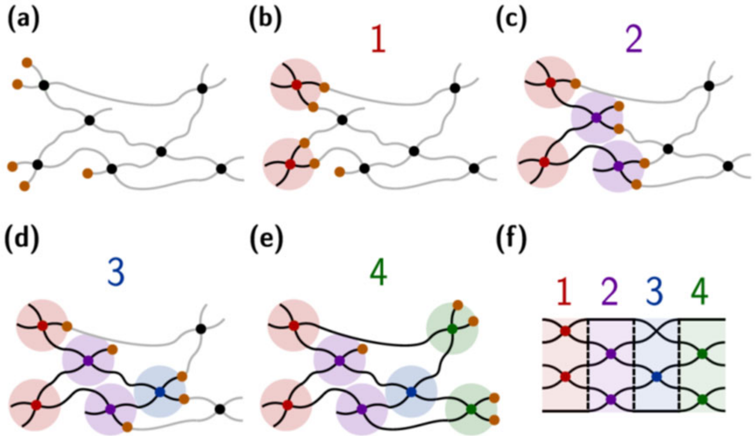
Universal SVD architecture for matrix multiplications



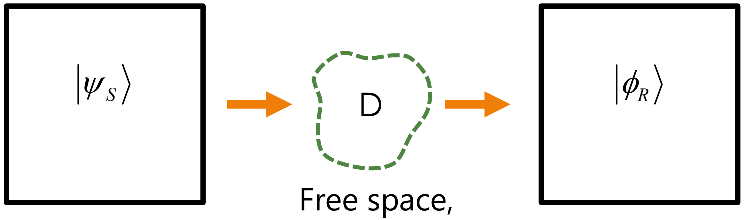
Finding best channels

Introduction

- New mathematical and physical descriptions now support these new kinds of optical systems
  - a new topological understanding and associated algorithms
  - a new, “modal” view of optics
    - beyond conventional resonator and propagating modes
    - and even classic “beams”
- This new “modal” approach is also fundamentally important in optics
  - mapping well to these new circuits as well as previous optics



S. Pai, I. A. D. Williamson, T. W. Hughes, M. Minkov, O. Solgaard, S. Fan, and D. A. B. Miller, "Parallel programming of an arbitrary feedforward photonic network," IEEE J. Sel. Top. Quantum Electron. 25, 6100813 (2020)



Source or input volume or space

Free space, device, object or scatterer

Receiving or output volume or space

D. A. B. Miller, "Waves, modes, communications, and optics: a tutorial," Adv. Opt. Photon. 11, 679-825 (2019)

Summary

Introduce ideas of

programmable, self-configuring, and self-stabilizing complex interferometric circuits

and first areas of applications being explored

Briefly introduce the new “modal” way of looking at optics

which also helps us understand these systems and what they can do

References

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For a broad review of such circuits see
W. Bogaerts et al., “Programmable photonic circuits,”
Nature 586, 207 (2020)

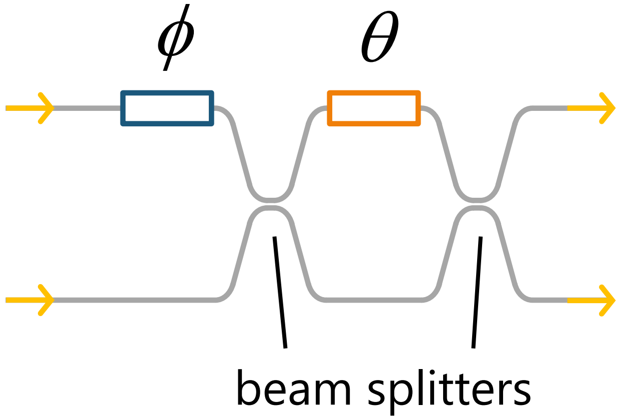
For understanding the new modal approach to optics see

D. Miller, "Waves, modes, communications, and optics: a tutorial," Adv. Opt. Photon. 11, 679 (2019)

A simple self-configuring circuit – the self-aligning beam coupler

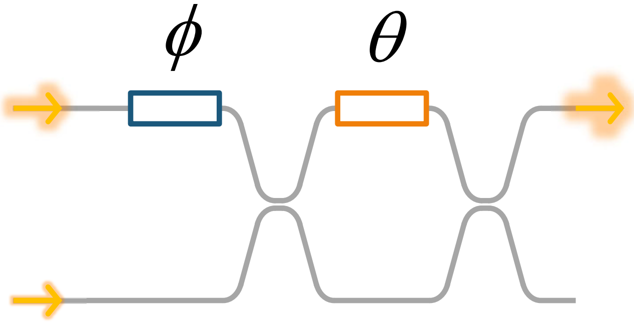
Nulling a Mach-Zehnder output

- Consider a waveguide Mach-Zehnder interferometer (MZI)
  - formed from two “50:50” beam splitters
  - and at least two phase shifters
    - one, ϕ, to control the relative phase of the two inputs
    - a second, θ, to control the relative phase on the interferometer “arms”

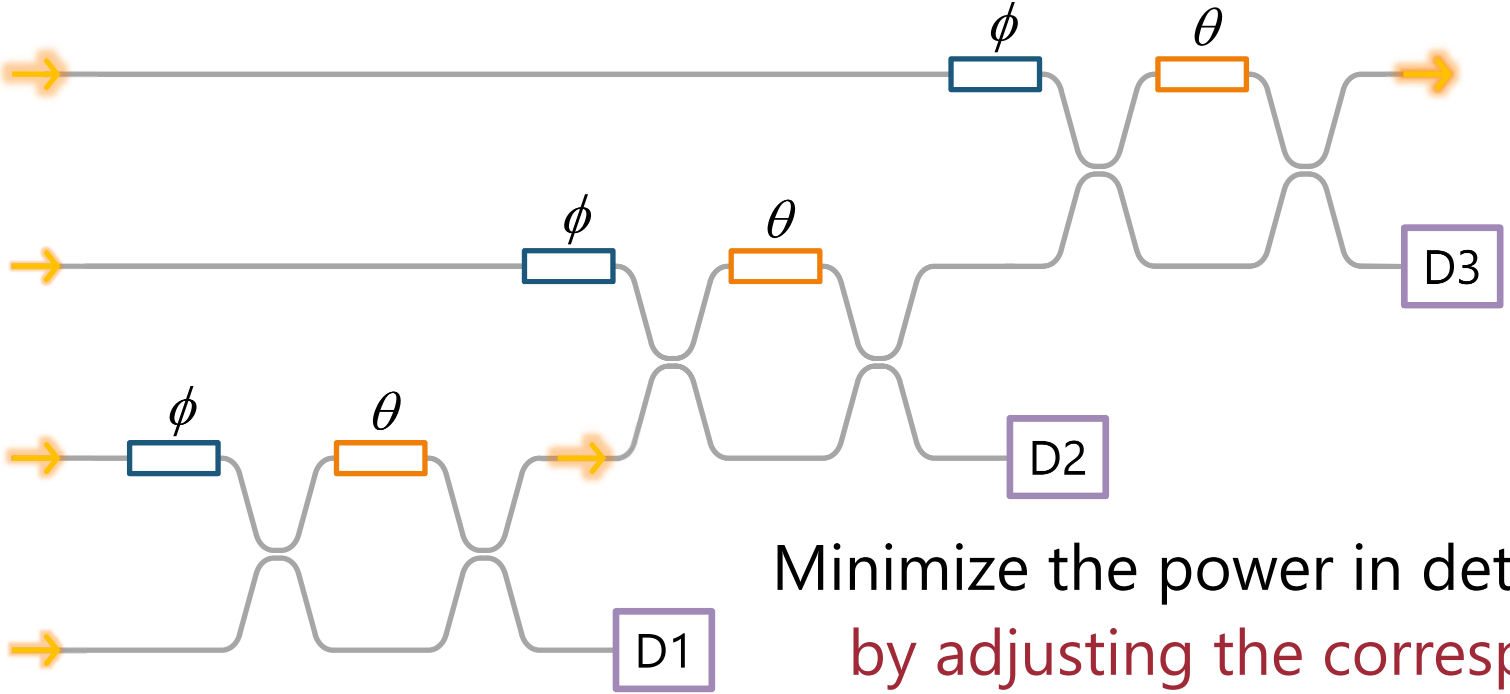


Nulling a Mach-Zehnder output

In such an MZI with 50:50 beamsplitters
- for any relative input amplitudes and phases
  - we can "null" out the power at the bottom output
    - by two successive single-parameter power minimizations
      - first, using ϕ
      - second, using θ



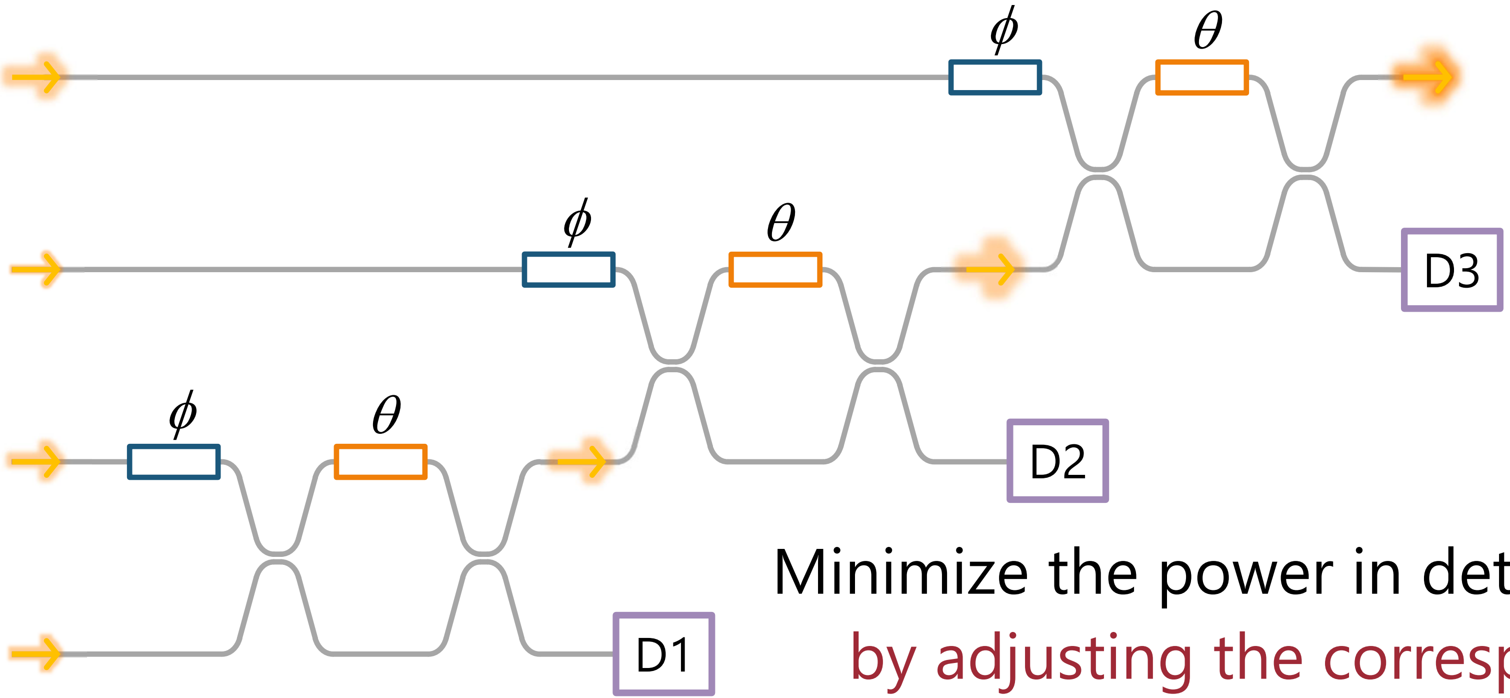
"Diagonal line" self-aligning coupler



Minimize the power in detector D1
by adjusting the corresponding ϕ
and then θ
putting all power in the upper output

"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

“Diagonal line” self-aligning coupler



Minimize the power in detector D2

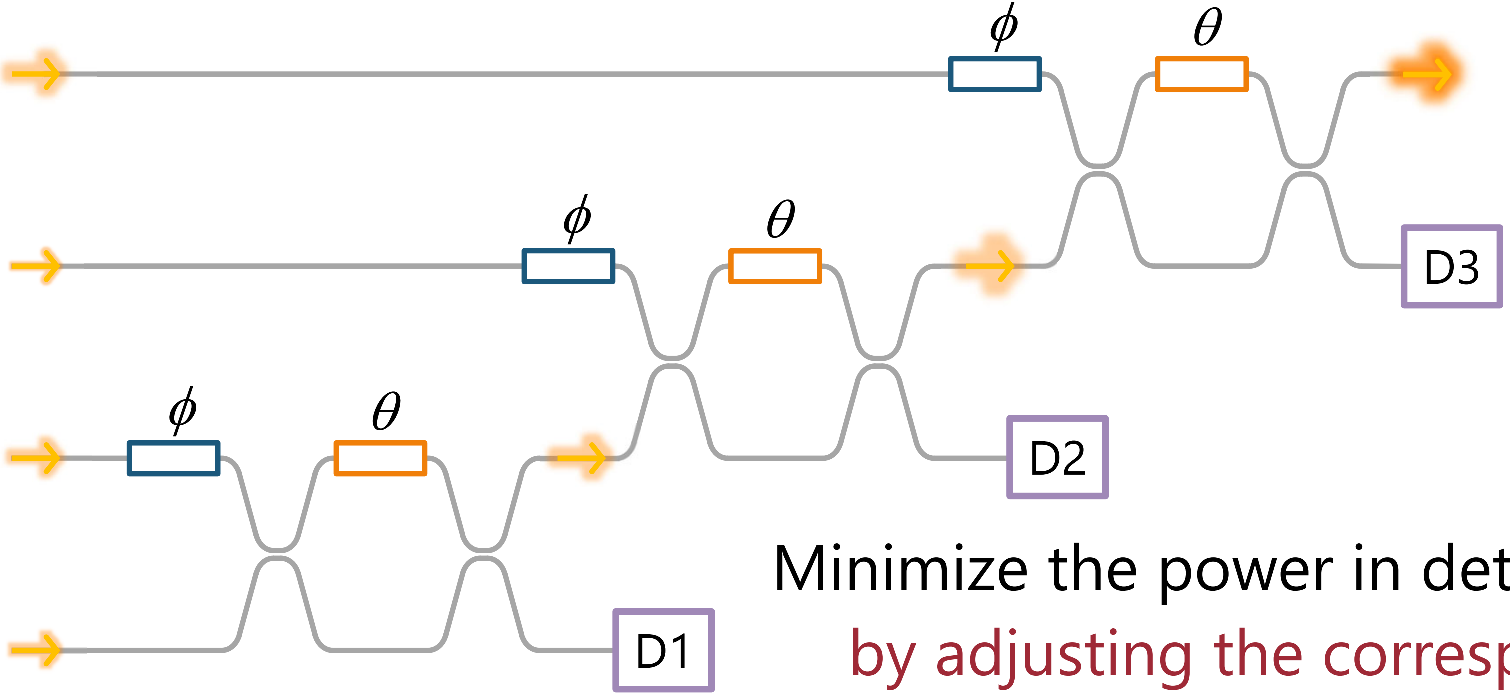
by adjusting the corresponding ϕ

and then θ

putting all power in the upper output

“Self-aligning universal beam coupler,” Opt. Express **21**, 6360 (2013)

"Diagonal line" self-aligning coupler



Minimize the power in detector D3

by adjusting the corresponding ϕ

and then θ

putting all power in the upper output

"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

Self-aligning beam coupler

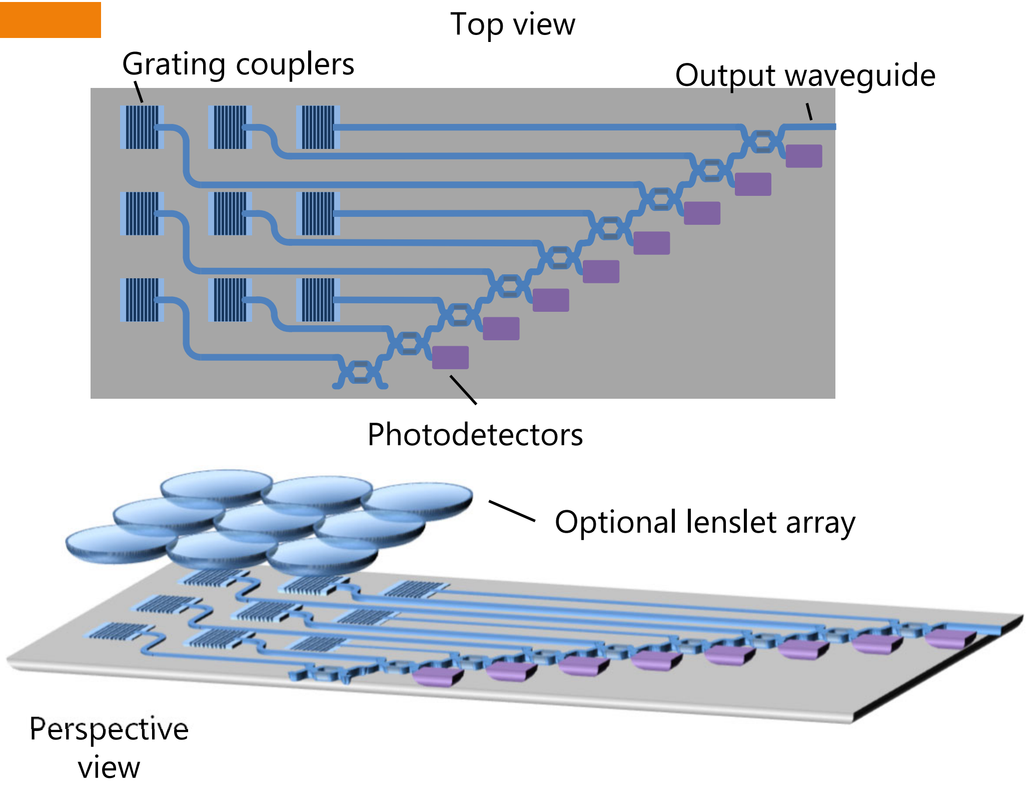
Grating couplers could couple a free-space beam to a set of waveguides

Then

- we could automatically couple all the power to the one output guide

This could run continuously

- tracking changes in the beam

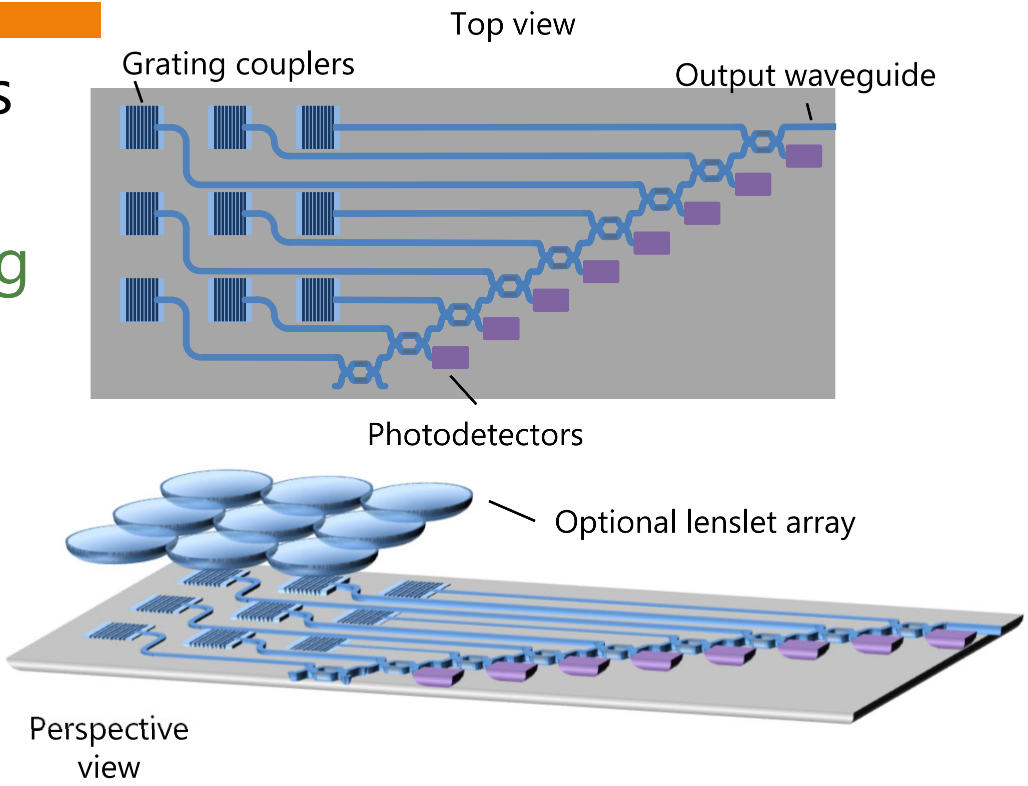


"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

Self-aligning beam coupler

This has several different uses

- tracking an input source both in angle and focusing
- correcting for aberrations
- analyzing amplitude and phase of the components of a beam
  - …



"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

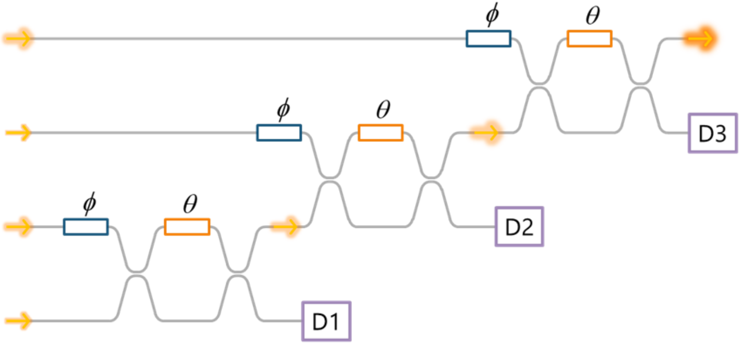
“Diagonal line” self-aligning coupler

Note this works

- without calculations
- without calibrations

The computation to set up this system

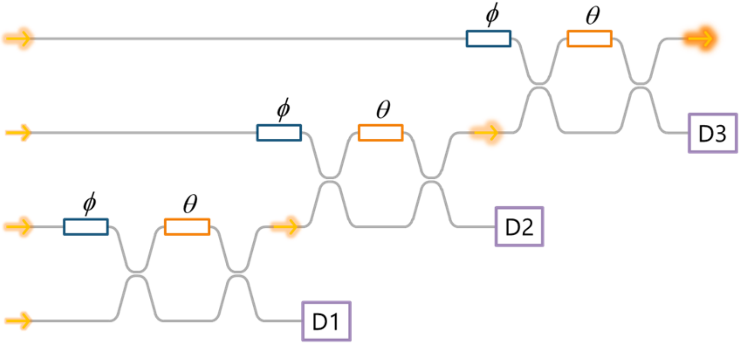
- is physically performed by the system itself
  - which is nonlinear because of the feedback loops from detectors to phase shifters



“Self-aligning universal beam coupler,” Opt. Express **21**, 6360 (2013)

“Diagonal line” self-aligning coupler

- This kind of simple progressive algorithm
  - only works for certain topologies of networks though
    - we understand this topology well
      - and it is a branch of graph theory
- It is remarkable that we have a complex nonlinear system
  - that nonetheless supports simple control and configuration algorithms
    - that lead to stable and convergent systems



“Self-aligning universal beam coupler,” Opt. Express **21**, 6360 (2013)

Some practical points about silicon photonic circuits

- These silicon photonics circuits are typically made in foundries, such as
  - AMF, AIM, IMEC, …
    - and many support multi-project wafers for university groups
- Simple experimental circuits typically use small numbers of “ports”
  - e.g., 4, 9, 16
    - though circuits have been made with many hundreds of interferometers
- Phase shifting is typically done by heating up waveguide sections ~ 100 microns long
  - which takes milliwatts of power
- Micromechanical phase shifters are under research and development
  - and would eliminate such powers
- Such phase shifters have response times ~ milliseconds to microseconds
- Faster phase shifters are possible
  - though they may be larger

Example early work on mesh optics

Early experimental mesh demonstrations

- J. Carolan, C. Harrold, C. Sparrow, E. Martín-López, N. J. Russell, J. W. Silverstone, P. J. Shadbolt, N. Matsuda, M. Oguma, M. Itoh, G. D. Marshall, M. G. Thompson, J. C. F. Matthews, T. Hashimoto, J. L. O'Brien, and A. Laing, "Universal linear optics," Science 349, 711-716 (2015)
- L. Zhuang, C. G. H. Roeloffzen, M. Hoekman, K.-J. Boller, and A. J. Lowery, "Programmable photonic signal processor chip for radiofrequency applications," Optica 2, 854-859 (2015)
- D. Pérez, I. Gasulla, J. Capmany, and R. A. Soref, "Reconfigurable lattice mesh designs for programmable photonic processors," Opt. Express 24, 12093-12106 (2016)
- Y. Shen, N. C. Harris, S. Skirlo, M. Prabhu, T. Baehr-Jones, M. Hochberg, X. Sun, S. Zhao, H. Larochelle, D. Englund, and M. Soljacic, "Deep Learning with Coherent Nanophotonic Circuits," Nature Photonics 11, 441-446 (2017)
- N. C. Harris, G. R. Steinbrecher, J. Mower, Y. Lahini, M. Prabhu, D. Bunandar, C. Chen, F. N. C. Wong, T. Baehr-Jones, M. Hochberg, S. Lloyd, and D. Englund, "Quantum transport simulations in a programmable nanophotonic processor," Nature Photonics 11, 447-452 (2017)

Self-configuring and self-correcting optics demonstrations

- A. Ribeiro, A. Ruocco, L. Vanacker, and W. Bogaerts, "Demonstration of a 4 × 4-port universal linear circuit," Optica 3, 1348-1357 (2016)
- C. M. Wilkes, X. Qiang, J. Wang, R. Santagati, S. Paesani, X. Zhou, D. A. B. Miller, G. D. Marshall, M. G. Thompson, and J. L. O'Brien, "60 dB high-extinction auto-configured Mach–Zehnder interferometer," Opt. Lett. 41, 5318-5321 (2016)
- A. Annoni, E. Guglielmi, M. Carminati, G. Ferrari, M. Sampietro, D. A. B. Miller, A. Melloni, and F. Morichetti, "Unscrambling light – automatically undoing strong mixing between modes," Light Science & Applications 6, e17110 (2017)

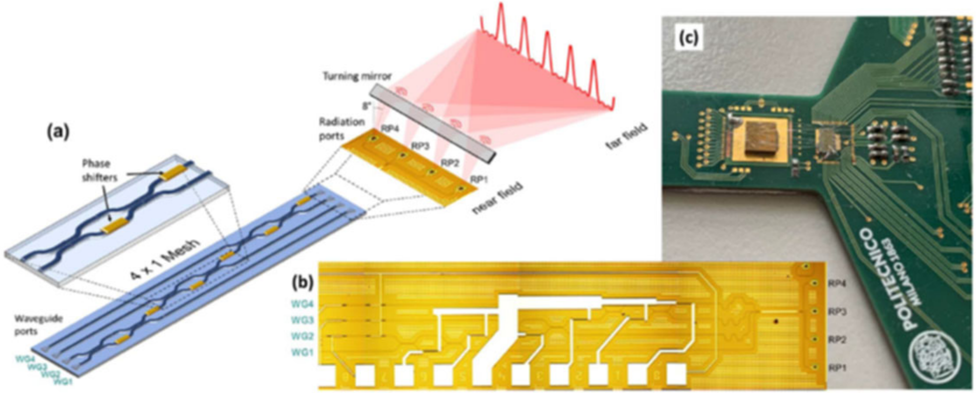
Theory of universal and self-configuring/correcting optics

- DM, "Self-aligning universal beam coupler," Opt. Express 21, 6360-6370 (2013)
- DM, "Self-configuring universal linear optical component," Photon. Res. 1, 1-15 (2013)
- DM, "Perfect optics with imperfect components," Optica 2, 747-750 (2015)

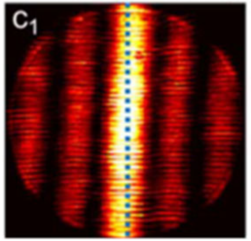
Pre-compensating a beam

Removing the effects of a diffusing mask with a mesh

1. optimize the mesh to maximize intensity in the center of the camera



No mask (mesh off)



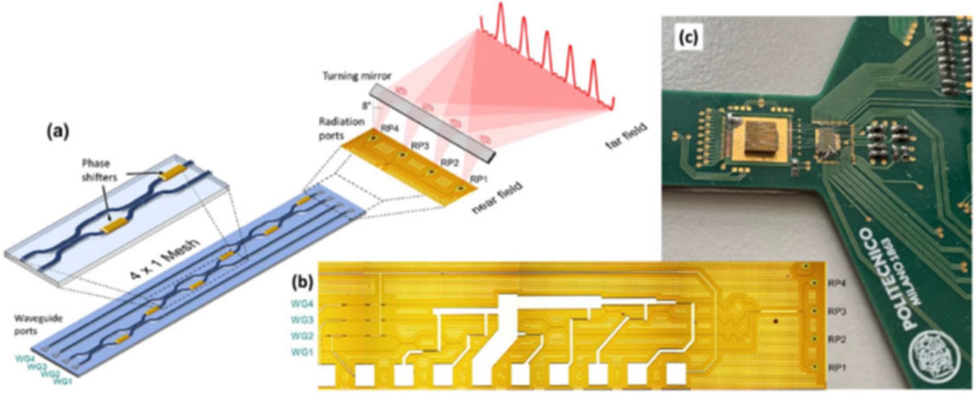
M. Milanizadeh, F. Toso, G. Ferrari, T. Jonuzi, D. A. B. Miller, A. Melloni, and F. Morichetti, "Coherent self-control of free-space optical beams with integrated silicon photonic meshes,". Photonics Research 9, 2196-2204 (2021)

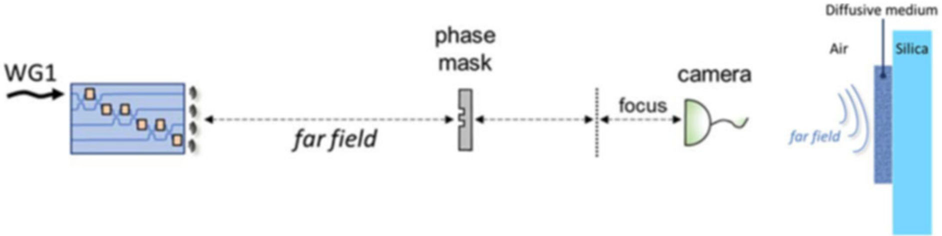
Pre-compensating a beam

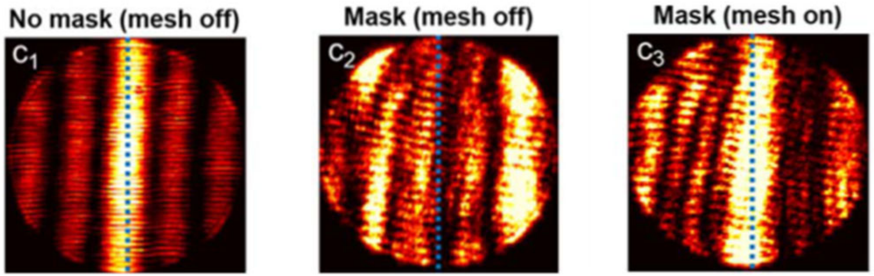
Removing the effects of a diffusing mask with a mesh

1. optimize the mesh to maximize intensity in the center of the camera
2. introduce a diffusing phase mask
3. re-optimize the mesh settings to restore the central maximum

M. Milanizadeh, F. Toso, G. Ferrari, T. Jonuzi, D. A. B. Miller, A. Melloni, and F. Morichetti, "Coherent self-control of free-space optical beams with integrated silicon photonic meshes,". Photonics Research 9, 2196-2204 (2021)







Optimization methods

In addition to simple progressive algorithms
- which work for certain architectures
  - and can be optimally fast
    - requiring the minimum possible number of measurements

other optimization approaches are possible
- such as standard global optimization algorithms
  - and minimization approaches based on “dithering” individual phase shifters

Anecdotally, it appears that such optimization
- both with progressive and global algorithms
  - can lead to good performance
    - even with imperfect components
      - e.g., imperfect split ratios in beamsplitters

A new kind of optics – separating overlapping beams without (fundamental) loss

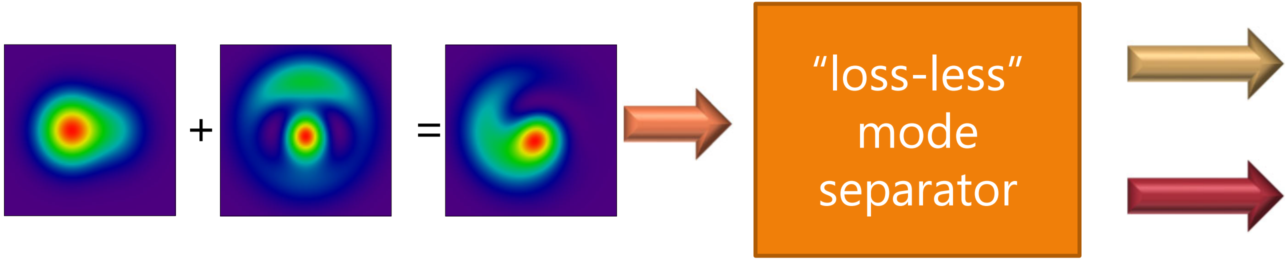
Example - Separating overlapping beams

In situations with

fixed

highly symmetric beams

there are good specific low-loss separation solutions



“loss-less” mode separator

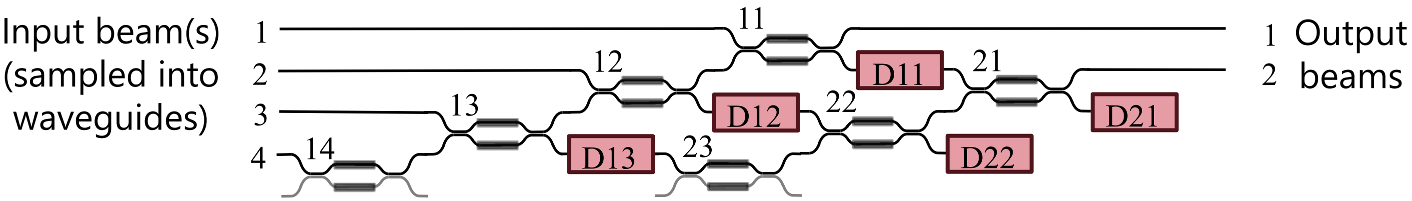
But for general cases

of lower symmetry and/or higher complexity

or where the beams change in time

general solutions have not been known

Separating multiple orthogonal beams



"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

Once we have aligned beam 1 to output 1 using detectors D11 – D13

an orthogonal input beam 2 would pass entirely into the detectors D11 – D13

If we make these detectors mostly transparent

this second beam would pass into the second diagonal "row"

where we self-align it to output 2 using detectors D21 – D22

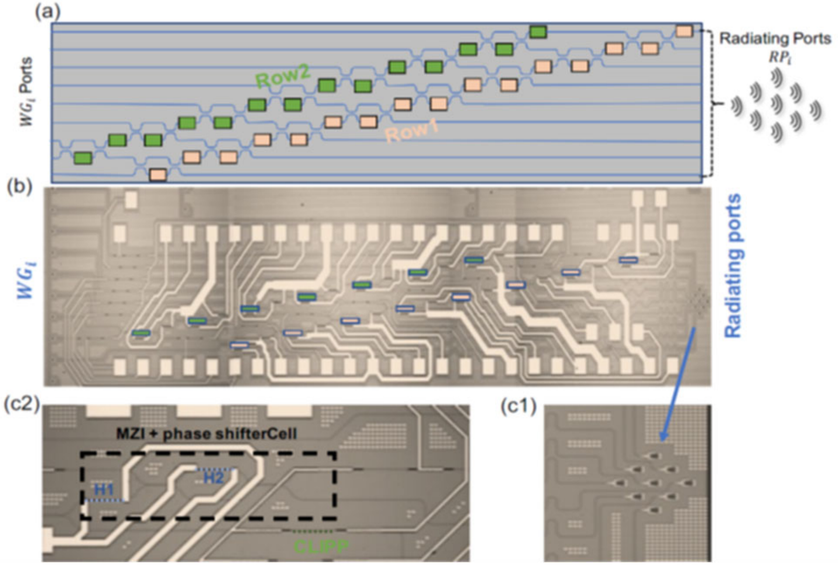
separating two overlapping orthogonal beams to separate outputs

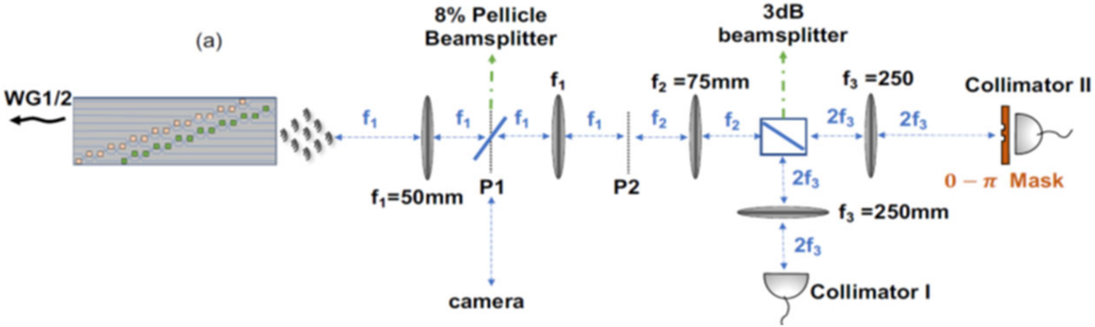
Separating free-space modes

9x2 diagonal line mesh

- separates two orthogonal free-space input modes
- automatically by self-configuration

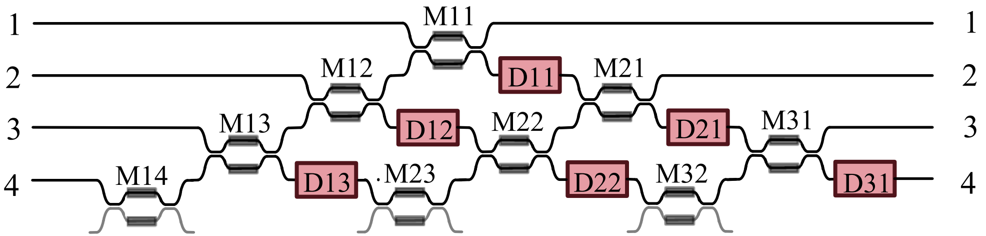
M. Milanizadeh, SM. SeyedinNavadeh, F. Zanetto, V. Grimaldi, C. De Vita, C. Klitis, M. Sorel, G. Ferrari, D. A. B. Miller, A. Melloni, and F Morichetti, "Separating arbitrary free-space beams with an integrated photonic processor," Light: Science & Applications 11, 197 (2022)





Separating multiple orthogonal beams

Input beam(s)
(sampled into
waveguides)



Output
beams

"Self-aligning
universal beam
coupler," Opt.
Express **21**, 6360
(2013)

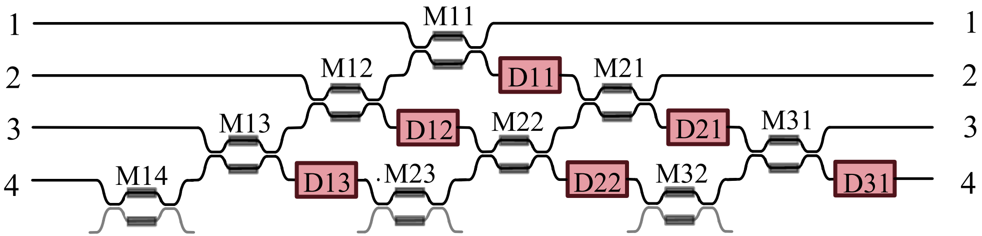
Adding more rows and self-alignments

separates a number of orthogonal beams

equal to the number of beam "segments", here, 4

Automatically undoing scattering among multiple modes

Separating multiple orthogonal beams



Input beam(s) (sampled into waveguides)

Output beams

"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

If we put identifying "tones" on each orthogonal input "beam"

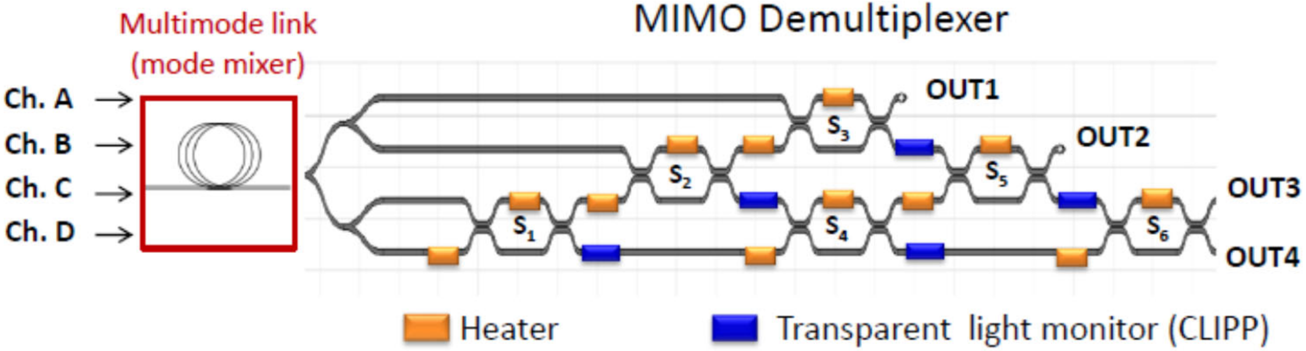
and have the corresponding diagonal row of detectors look for that tone

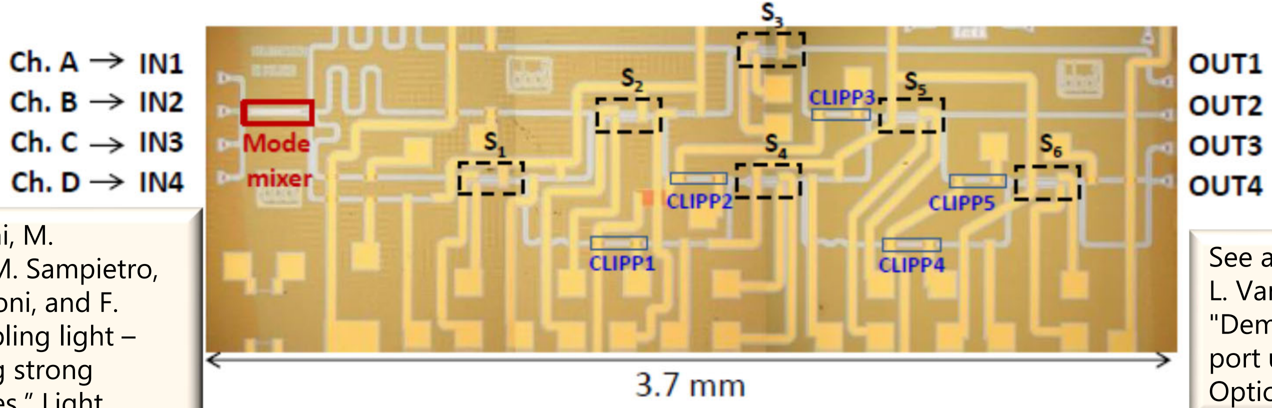
then the mesh can continually adapt to the orthogonal inputs

even when they are all present at the same time

and even if they change

Integrated MIMO demultiplexer: technology





A. Annoni, E. Guglielmi, M. Carminati, G. Ferrari, M. Sampietro, D. A. B. Miller, A. Melloni, and F. Morichetti, “Unscrambling light – automatically undoing strong mixing between modes,” Light Science & Applications 6, e17110 (2017)

See also A. Ribeiro, A. Ruocco, L. Vanacker, and W. Bogaerts, "Demonstration of a 4 × 4-port universal linear circuit," Optica 3, 1348-1357 (2016)

- Transparent detectors required for sequential tuning
- CLIPP-assisted circuit reconfiguration & feedback control

Si chip fabricated by CEA-Leti

Speed of mesh self-configuration

This analysis

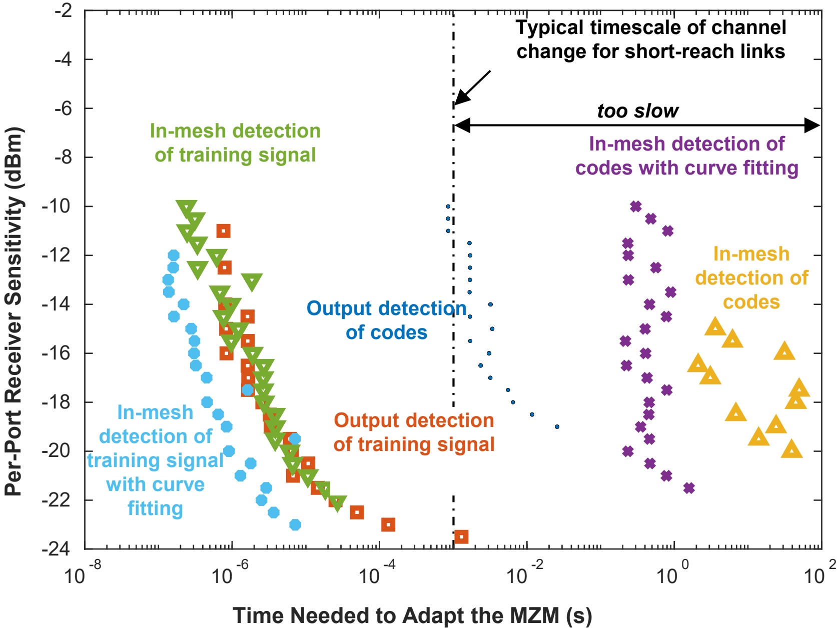
comparing several minor variants of the detection approach

shows that, even with only 10’s of microwatts of input powers

entire networks (e.g., 4x4) can self-configure in microseconds or less

So, fast enough for

- km-scale multimode fiber optics
- free-space turbulence compensation
- rapid configuration for mathematical problems



K. Choutagunta, I. Roberts, D. A. B. Miller, and J. M. Kahn, “Adapting Mach-Zehnder Mesh Equalizers in Direct-Detection Mode-Division-Multiplexed Links,” J. Lightwave Technol. 38, 723 (2020)

Topology of mesh architectures

Mathematics and meshes

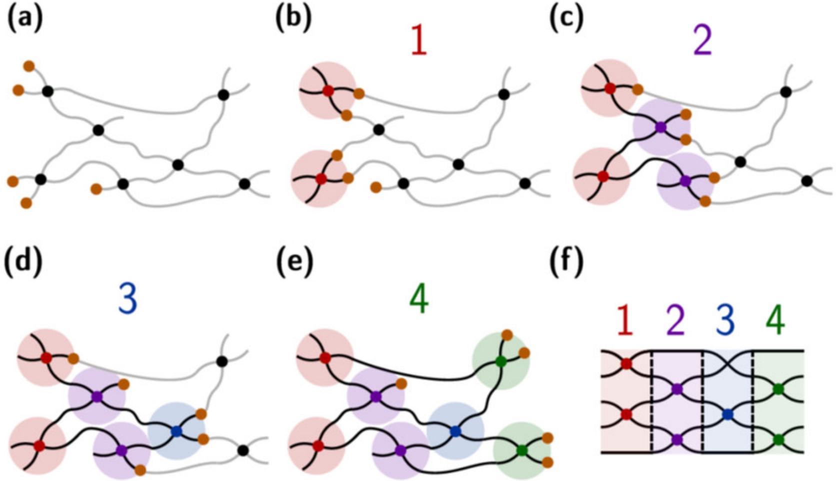
Different mathematical concepts

such as graph theory

are starting to appear in discussions of optics

e.g., directed acyclic graphs

which correspond to "forward-only" circuits



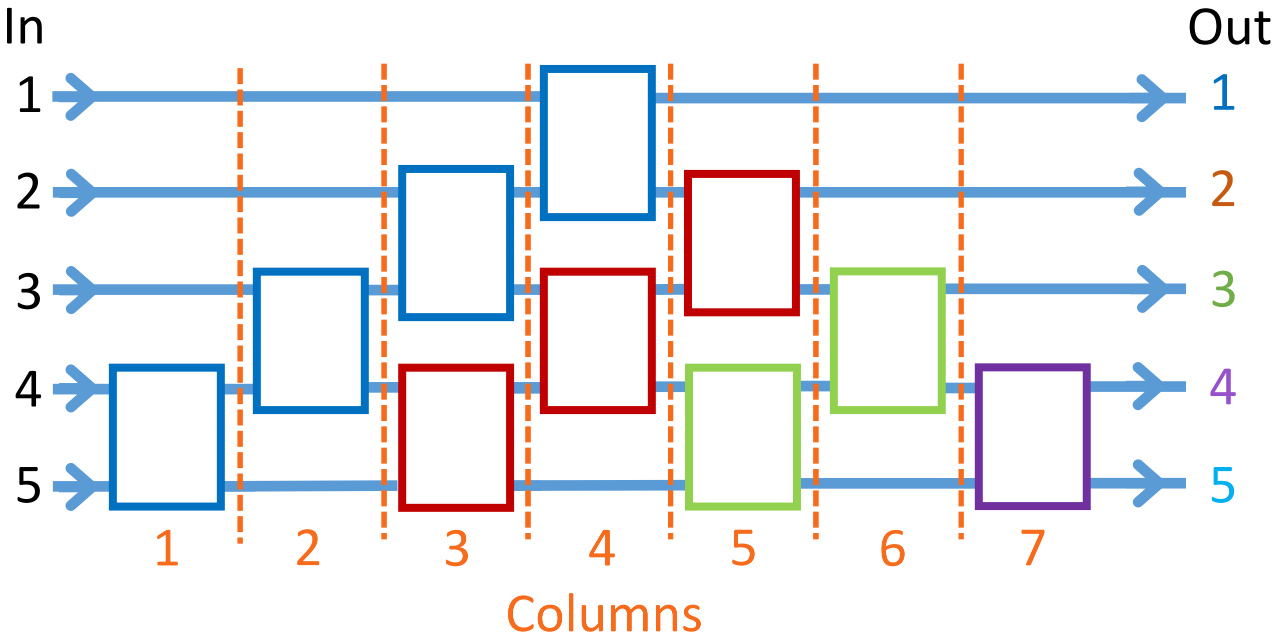
Topological sorting of an optical network into columns for parallel configuration

See also X. Chen et al, "Graph representations for programmable photonic circuits," J. Lightwave Technol. 38, 4009 (2020)

S. Pai et al., "Parallel programming of an arbitrary feedforward photonic network," IEEE J. Sel. Top. Quantum Electron. 25, 6100813 (2020)

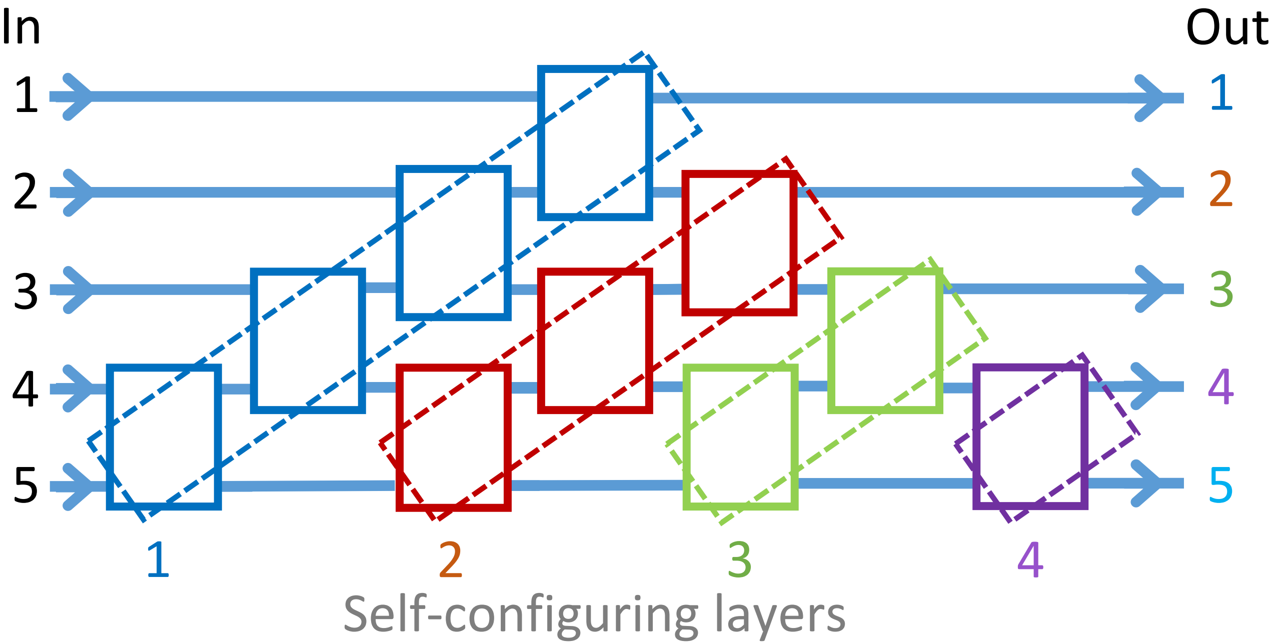
Column topology

“Columns” can be identified with a simple topological algorithm and configured or calibrated in parallel



Self-configuring layer topology

"Self-configuring layers" have one connection path through 2x2 blocks from their output to each of their inputs



Applications of self-configuring mesh circuits

Other applications and extensions

- phase conjugation
- undoing scattering

  including potential real-time self-configuration

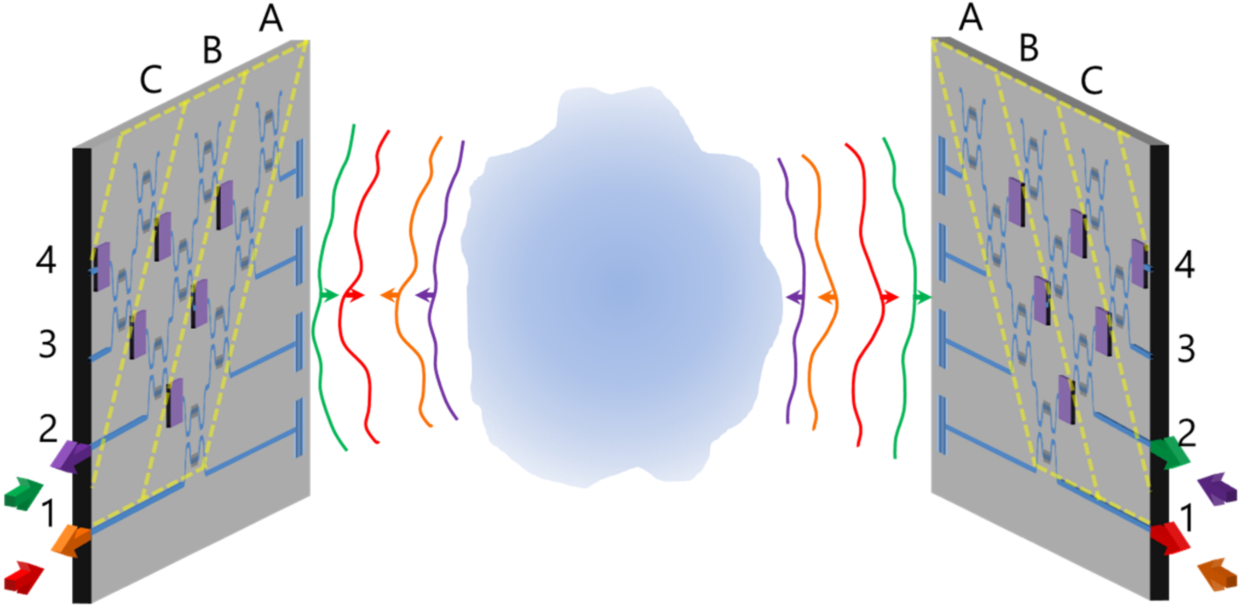
  e.g., for undoing atmospheric turbulence or mode scattering in fibers
- finding the best channels for communications
- self-calibrating, self-correcting and self-stabilizing complex optical systems

Establishing optimum orthogonal channels

Iterating back and forward between the two sides

finds the optimal orthogonal channels through any scatterer

from the waveguides on the left to the waveguides on the right



"Establishing optimal wave communication channels automatically," J. Lightwave Technol. 31, 3987 (2013)

Establishing optimum orthogonal channels - experiment

System of two "facing" meshes

through simple optics

These can be misaligned

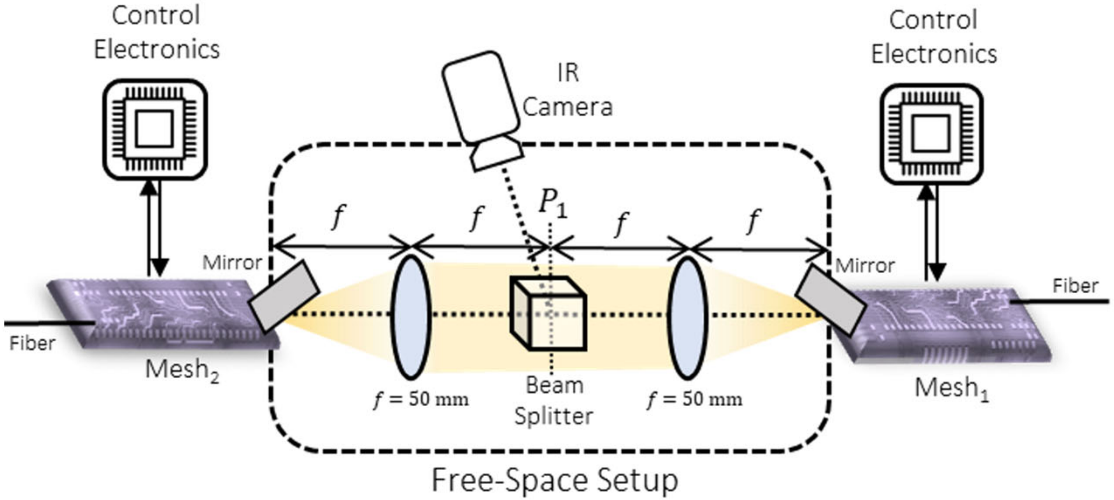
and we can introduce

aberrations or

partial blocking

in the path

The system still self-aligns to find the best, orthogonal channels

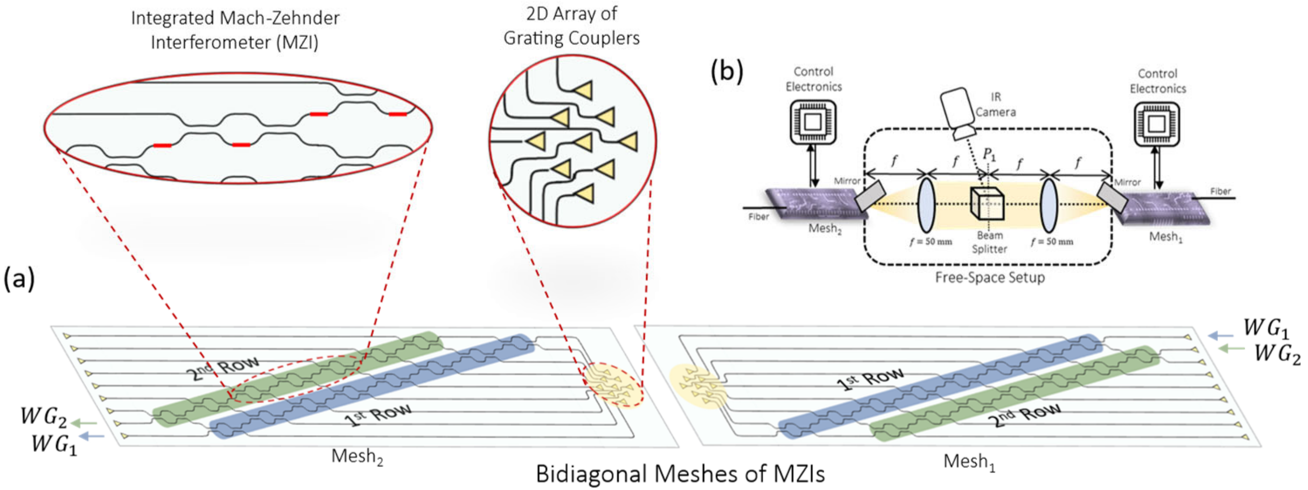


SM SeyedinNavadeh, M Milanizadeh, F Zanetto, V Grimaldi, C De Vita, G Ferrari, D A B Miller, A Melloni, F. Morichetti, "Multi-channel free-space optical communication between self-configuring silicon photonics meshes", ECIO22, 4-6 May 2022, Milan, Italy, Paper F.E.2

Establishing optimum orthogonal channels - experiment

Two “9x2” meshes allow automatic self-configuration

- signals in WG1 on the right can automatically be aligned to appear out of WG1 on the left, and, at the same time
- signals in WG2 on the right can automatically be aligned to appear out of WG2 on the left



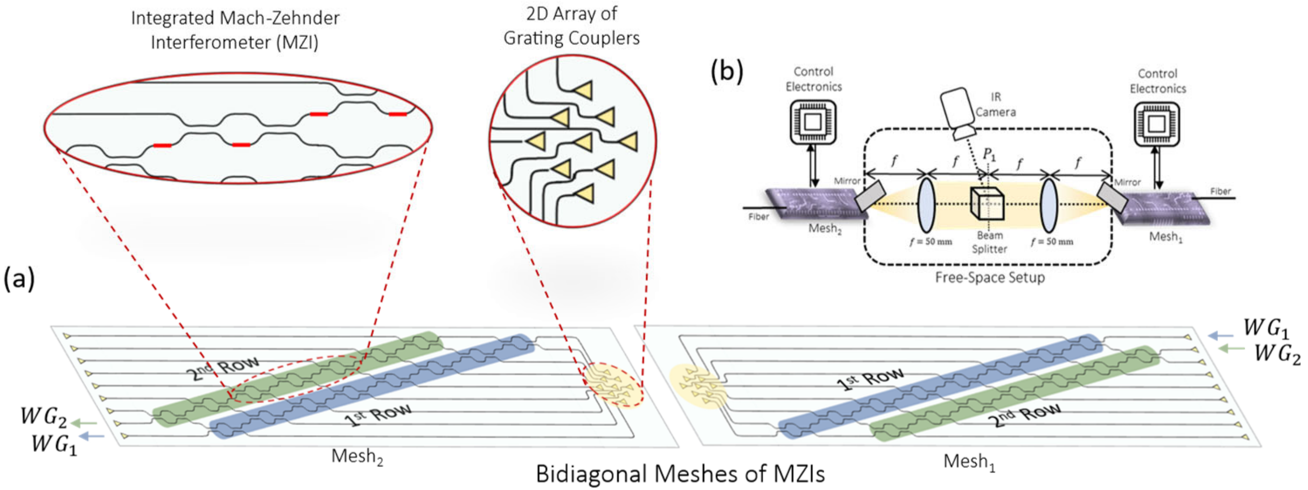
SM SeyedinNavadeh et al., ECIO22, Paper F.E.2

Establishing optimum orthogonal channels - experiment

Even after inserting a partially blocking mask in the optical path between the meshes

the system can re-establish orthogonal channels automatically

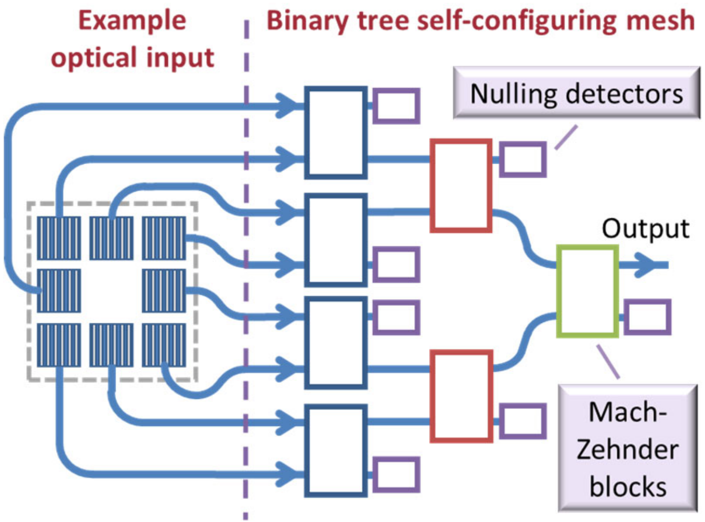
with > 30 dB rejection between the channels



SM SeyedinNavadeh et al., ECIO22, Paper F.E.2

Arbitrary beam generation and analysis

- Automatically analyze an arbitrary input beam
  - full amplitude and phase
    - by self-aligning a mesh
      - and calculating from the resulting settings
- Generate an arbitrary beam by running this network backwards



D. A. B. Miller, “Analyzing and generating multimode optical fields using self-configuring networks,” Optica 7, 794-801 (2020)

See also J. Bütow, J. S. Eismann, M. Milanizadeh, F. Morichetti, A. Melloni, D. A. B. Miller, and P. Banzer, "Spatially resolving amplitude and phase of light with a reconfigurable photonic integrated circuit," Optica 9, 939-946 (2022)

Universal matrix multiplier chip

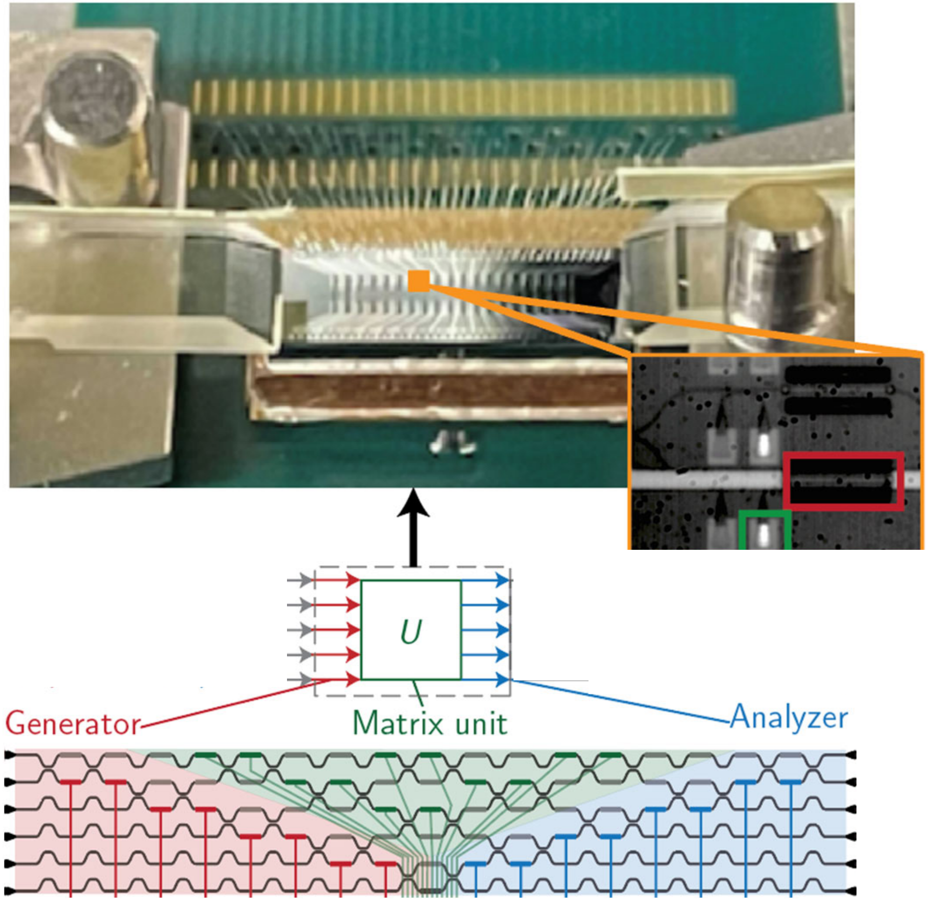
Universal and matrix multiplying chip

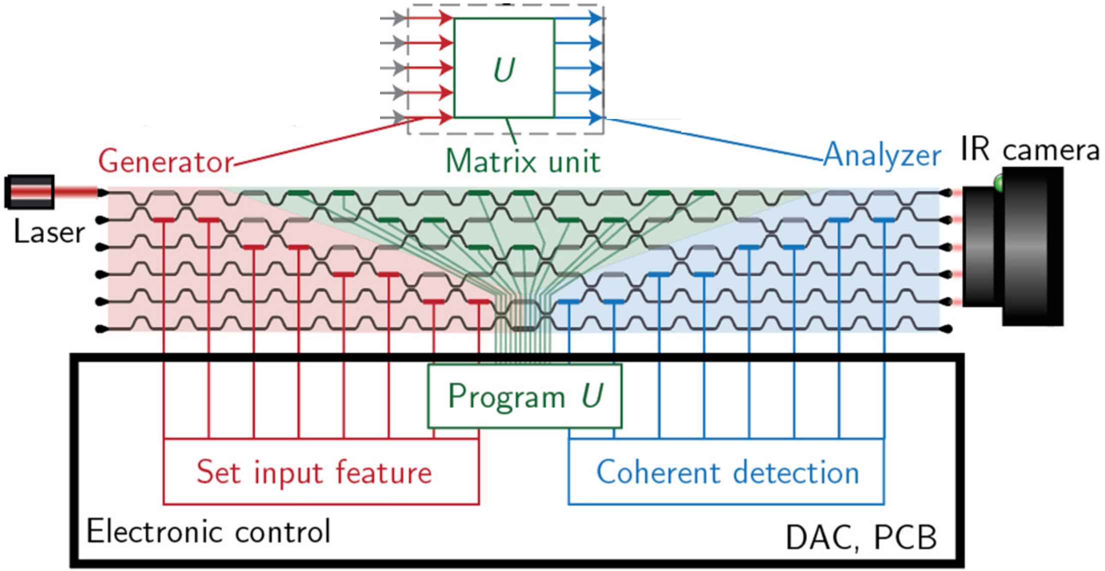
4x4 unitary Mach-Zehnder mesh with

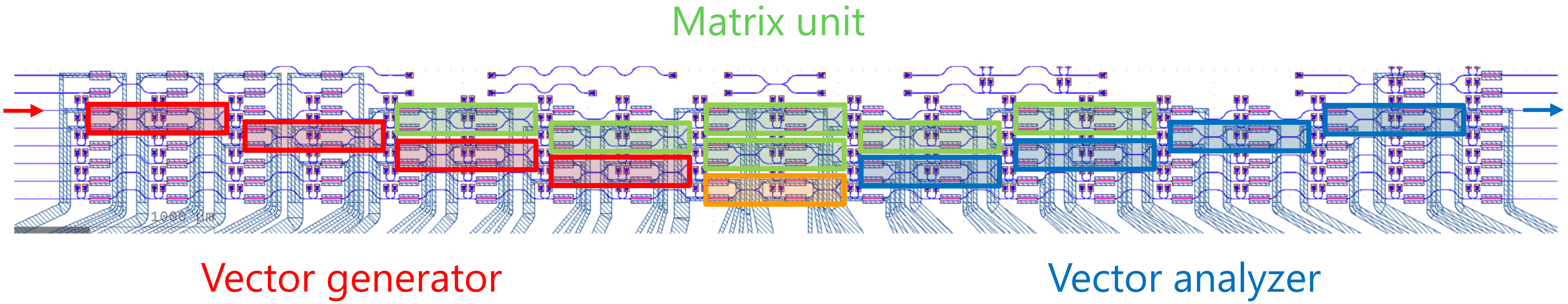
- monitors at every MZI output and on every MZI “arm”
- “generator” to create any complex input vector
- and “analyzer” to measure the complex output vector
- also allows full phase measurement from input to output

Note this design can keep all interferometric processes on chip

only an external input light source and final measuring power detectors are off-chip




U
Generator
Matrix unit
Analyzer
IR camera
Laser
Program U
Set input feature
Coherent detection
Electronic control
DAC, PCB


Matrix unit
1000 µm
Vector generator
Vector analyzer

Universal matrix multiplier chip

Full complex matrix multiplication

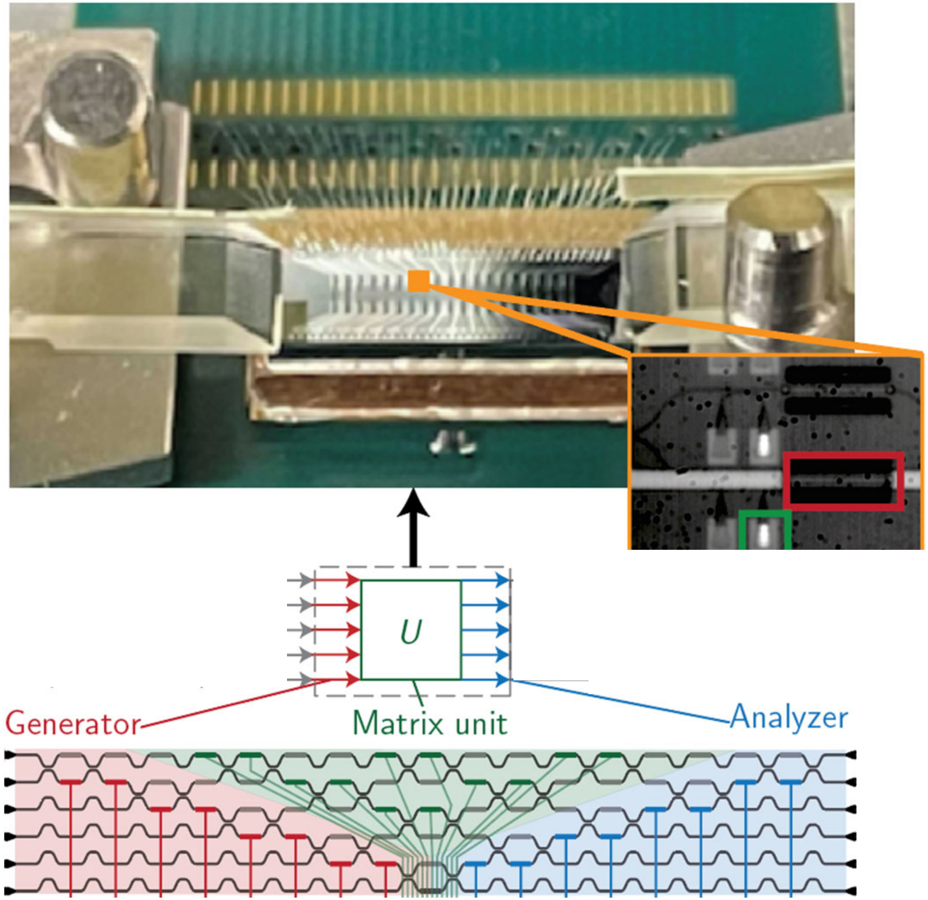
with vector generation and vector analysis

Photonic back-propagation neural net training

S. Pai, Z. Sun, T. W. Hughes, T. Park, B. Bartlett, I. A. D. Williamson, M. Minkov, M. Milanizadeh, N. Abebe, F. Morichetti, A Melloni, S. Fan, O. Solgaard, and D. A. B. Miller, “Experimentally realized in situ backpropagation for deep learning in nanophotonic neural networks,” DOI: 10.48550/arXiv.2205.08501

Digital matrix multiplication for cryptography

S. Pai, T. Park, M. Ball, B. Penkovsky, M. Milanizadeh, M Dubrovsky, N. Abebe, F. Morichetti, A. Melloni, S. Fan, O. Solgaard, and D. A.B. Miller “Experimental evaluation of digitally-verifiable photonic computing for blockchain and cryptocurrency,” DOI: 10.48550/arXiv.2205.08512



Other applications and extensions

- mathematical equation solving
- linear optical quantum circuits
- optical neural networks
- r.f. photonics
- new ways of sensing where we look for the features we want, and can adapt and program those to the application

  “superpixels”

    e.g., microscopy

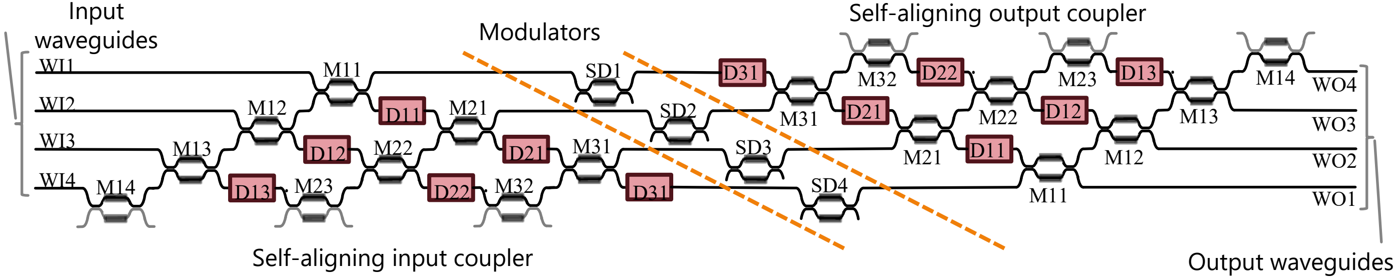
Universal self-configuing architectures

Universal self-configuring photonics

Universal architectures

- e.g., based on singular value decomposition (SVD)
  - allow any matrix multiplication
    - for arbitrary linear optics, neural networks, classical or quantum processing
  - and can be self-configured
    - and hence offer universal field-programmable linear arrays

General multiple mode converter



"Self-configuring universal linear optical component," Photon. Res. **1**, 1 (2013)

The self-aligning input coupler mesh on the left can couple any four orthogonal inputs

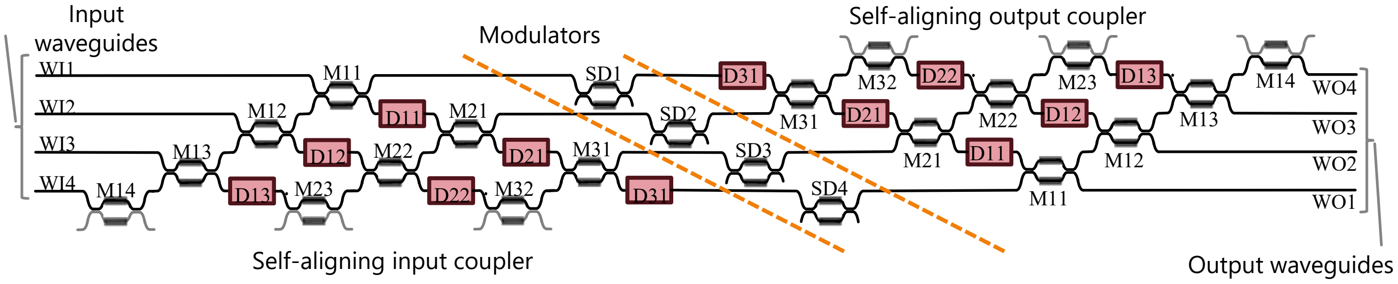
each to different single waveguides in the middle

Light in those single waveguides can be converted into any other set of four orthogonal outputs on the right

by the self-aligning output coupler mesh on the right

The amplitude and phase of this conversion can be controlled by the line of modulators in the middle

General multiple mode converter



"Self-configuring universal linear optical component," Photon. Res. **1**, 1 (2013)

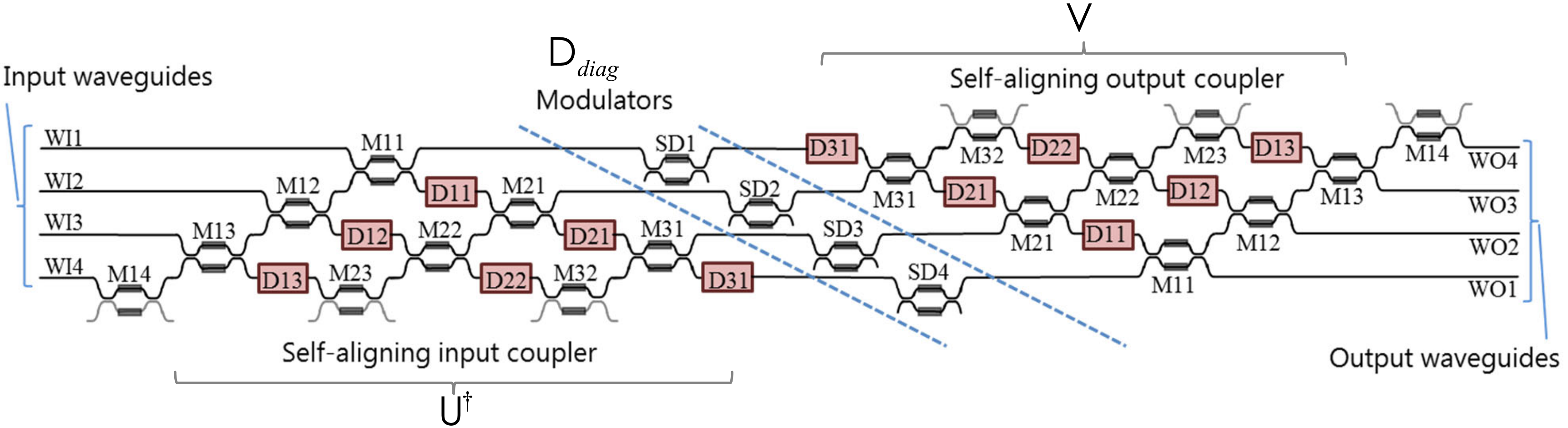
This kind of universal mode conversion, with such modulation

corresponds to being able to implement

an arbitrary (and non-unitary) matrix with such a mesh (at least if we do not require gain)

so this mesh is fully universal for performing any linear transformation

General multiple mode converter



The mathematical reason why this works is because

we can always perform the "singular value decomposition" of a matrix

which means a matrix D can always be written in the form

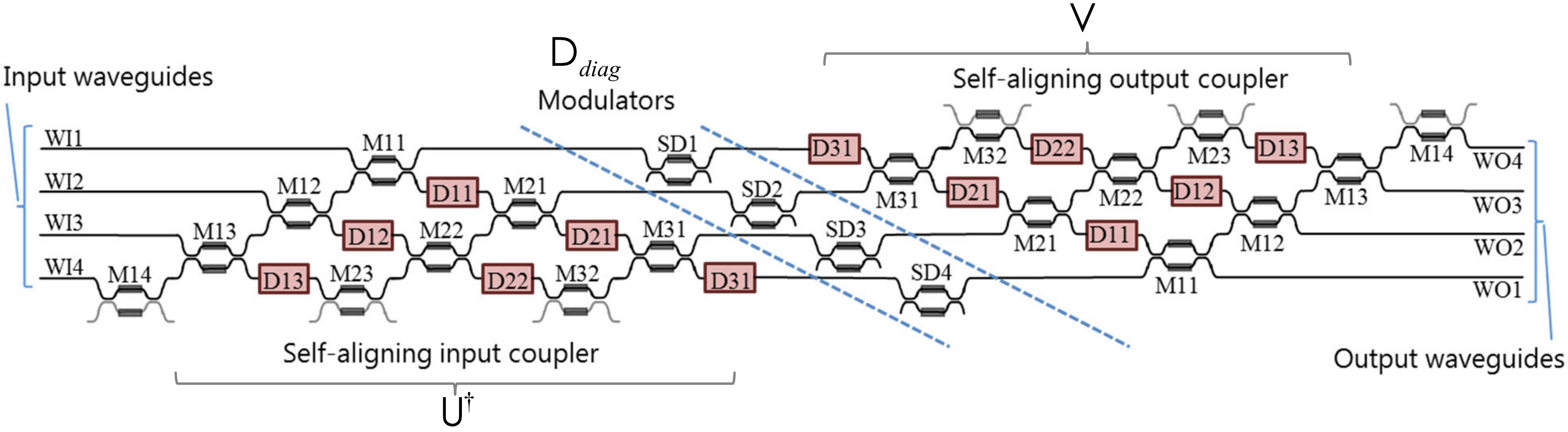
$$D = VD_{diag}U^\dagger$$

where U and V are "unitary" (lossless) matrices

and D_{diag} is a diagonal matrix

"Self-configuring universal linear optical component," Photon. Res. **1**, 1 (2013)

General multiple mode converter



The optical “units” in the mesh implement the singular value decomposition $D = VD_{diag}U^\dagger$

This is the first proof that any linear optical component is possible and that any linear optical system can be factored into a set of 2-beam interferences

This can be used in thought experiments for fundamental proofs

"Self-configuring universal linear optical component," Photon. Res. **1**, 1 (2013)

Waves, modes, and optics – viewing linear optics through singular-value decomposition

Decomposing optical systems

We can also flip this logic around

- We can always perform the singular value decomposition of an optical component or system
  - So any linear optical system can be described as a mode-converter

Opt. Express **20**, 23985 (2012)

These sets of modes turn out to have basic physical significance

Adv. Opt. Photon. 11, 679 (2019)

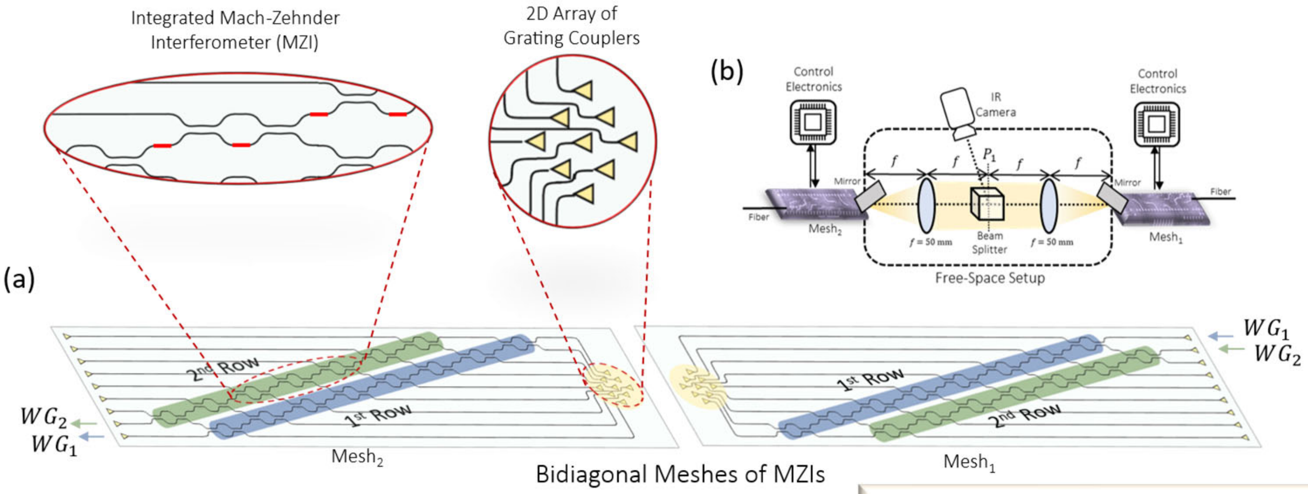
Establishing optimum orthogonal channels - experiment

The system of two “facing” chips is performing the singular-value decomposition of the optics, here for two channels, between

the inputs to the grating couplers on one side and

the outputs from the grating couplers on the other side

establishing the “communication modes” in the system



SM SeyedinNavadeh et al., ECIO22, Paper F.E.2

Waves, modes, communications and optics

"Waves, modes, communications and optics"
Adv. Opt. Photon. 11, 679-825 (2019)

For any linear optical system

- singular value decomposition gives
  - an optimal, orthogonal set of "input" functions that map, one-by-one, to an optimal orthogonal set of "output" functions

These allow

- ❑ A rigorous "communications mode" counting of communications channels
  - including the conclusion that there is always a finite number of usable channels
    - including specific new limits for various optical systems
- ❑ A general form of diffraction theory, valid for all sizes and shapes of objects
- ❑ The most economical "mode-converter basis" description of any linear optics
- ❑ New versions of Kirchhoff's radiation laws, valid for all objects
  - including nanophotonics and non-reciprocal systems …
- ❑ A new, "mode by mode" version of Einstein's A & B coefficient argument
- ❑ A new quantization of the radiation field in any volume

Conclusions

Conclusions

For a copy of these viewgraphs,
please e-mail dabm@stanford.edu

Self-configuring photonics enables complex circuits for new optics

The algorithms to calibrate and use these circuits are

simple and fast

The many uses of these ideas are just starting

These ideas also complement a fundamentally new way of looking at optics

the “communications modes” and “mode-converter basis sets” from singular value decomposition

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For a copy of these viewgraphs, please e-mail dabm@stanford.edu

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