Understanding and exploiting complex and self-configuring photonics

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Introduction

Silicon photonics allows remarkably complex interferometric optical circuits

- e.g., with 100’s or even 1000’s of components

Future devices and techonologies promise even larger numbers and densities

- e.g., exploiting nanophotonic structures

But could we get usable and controllable circuits with such large numbers of interferometric components

- and even if we did, could they do anything useful?

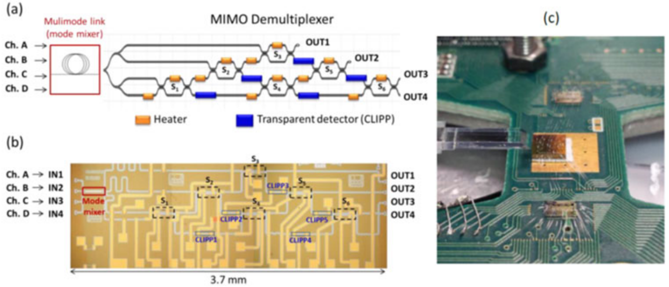
Introduction

In recent years, we have discovered architectures and algorithms that

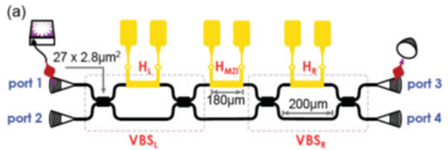
- allow control and programming of complex circuits
- automatically self-configure and self-stabilize
  - including adapting to problems that change in time

with many potential applications, e.g.,

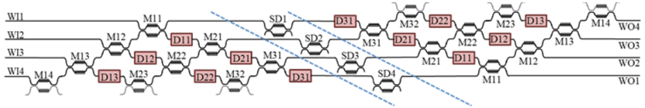
- communications
- information processing
- sensing

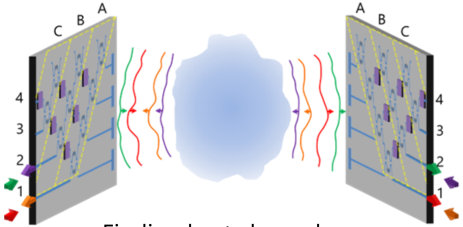


Automatic separation of mixed modes



Perfect optics from imperfect components


Universal SVD architecture for matrix multiplications

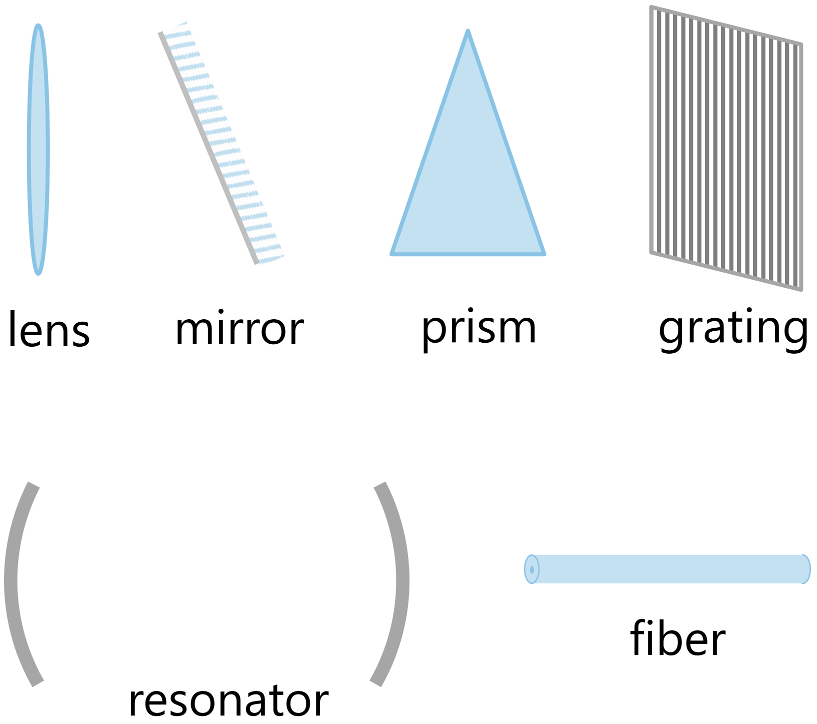


Finding best channels

Introduction

But, though these circuits are "optical components"

- they are not like any previous optics
  - such as the classical optics of
    - lenses, mirrors, prisms, and gratings
- nor are they well described by modal approaches
  - like
    - resonator modes or
    - propagating fiber modes



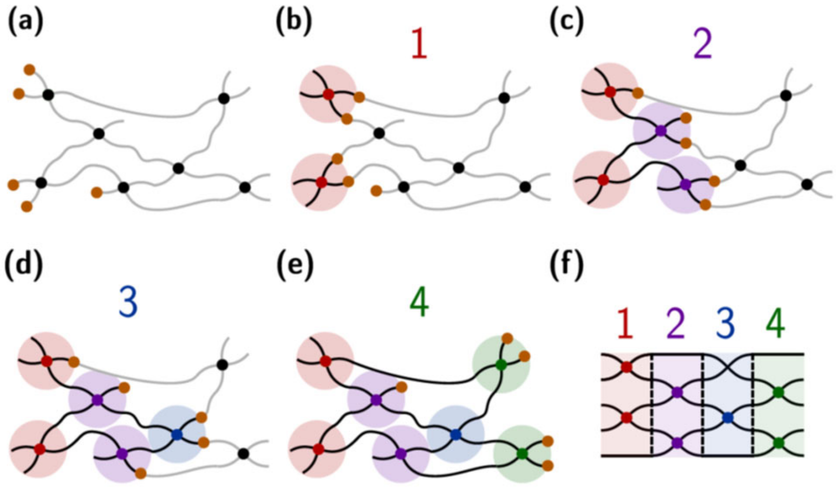
Introduction

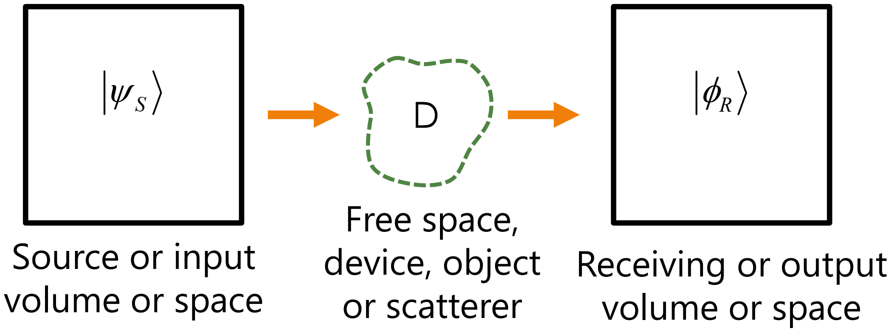
Fortunately, new mathematical and physical descriptions have emerged

- 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





Summary

Introduce ideas of

- complex but programmable and self-configuring 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

For a copy of these slides
e-mail dabm@stanford.edu

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)

See also
https://web.stanford.edu/group/dabmgroup/cgi-bin/dabm/
for other references and discussion

What we will and will not cover

We will concentrate on “forward-only” or “feed-forward” meshes of interferometers

We will not have time to discuss some other exciting related fields, including

- systems with frequency-dependent and/or recirculating elements
  - such as circuits contain rings, loops and/or backwards propagation
    - e.g., for wavelength-domain processing, and r.f. photonics
  - e.g., D. Marpaung, J. Yao, J. and J. Capmany, Nature Photon 13, 80 (2019),
  - W. Bogaerts et al., Nature 586, 207 (2020)
- multiplane light converters – another programmable approach to linear processors, especially for sorting modes
  - e.g., J. Carpenter, ECOC 2020, doi: 10.1109/ECOC48923.2020.9333331
  - V. Billault et al., Opt. Express 29, 33134 (2021)

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)

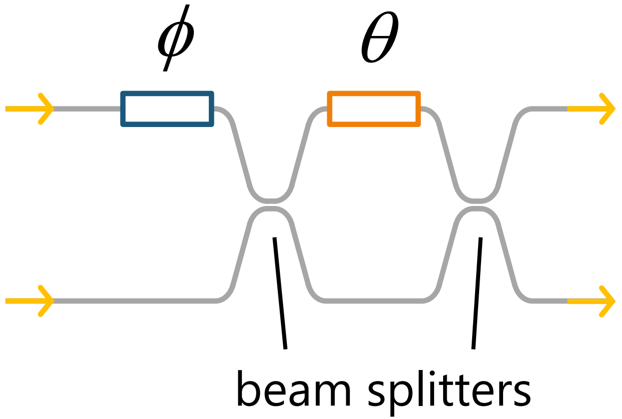
DM, "Self-configuring universal linear optical component," Photon. Res. 1, 1-15 (2013)

DM, "Perfect optics with imperfect components," Optica 2, 747-750 (2015)

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

Nulling a Mach-Zehnder output

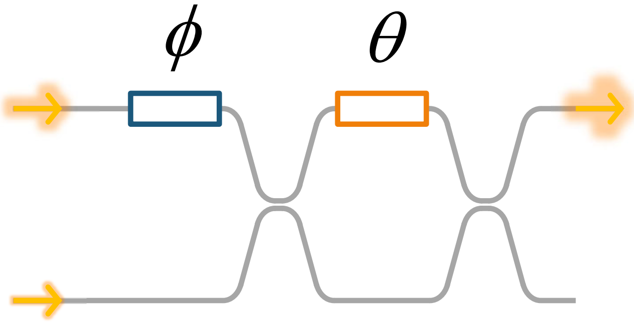
- Consider a waveguide Mach-Zehnder interferometer (MZI)
  - formed from two “50:50” beam splitters
  - and at least two phase shifters
    - one, ϕ, to control the relative phase of the two inputs
    - a second, θ, to control the relative phase on the interferometer “arms”



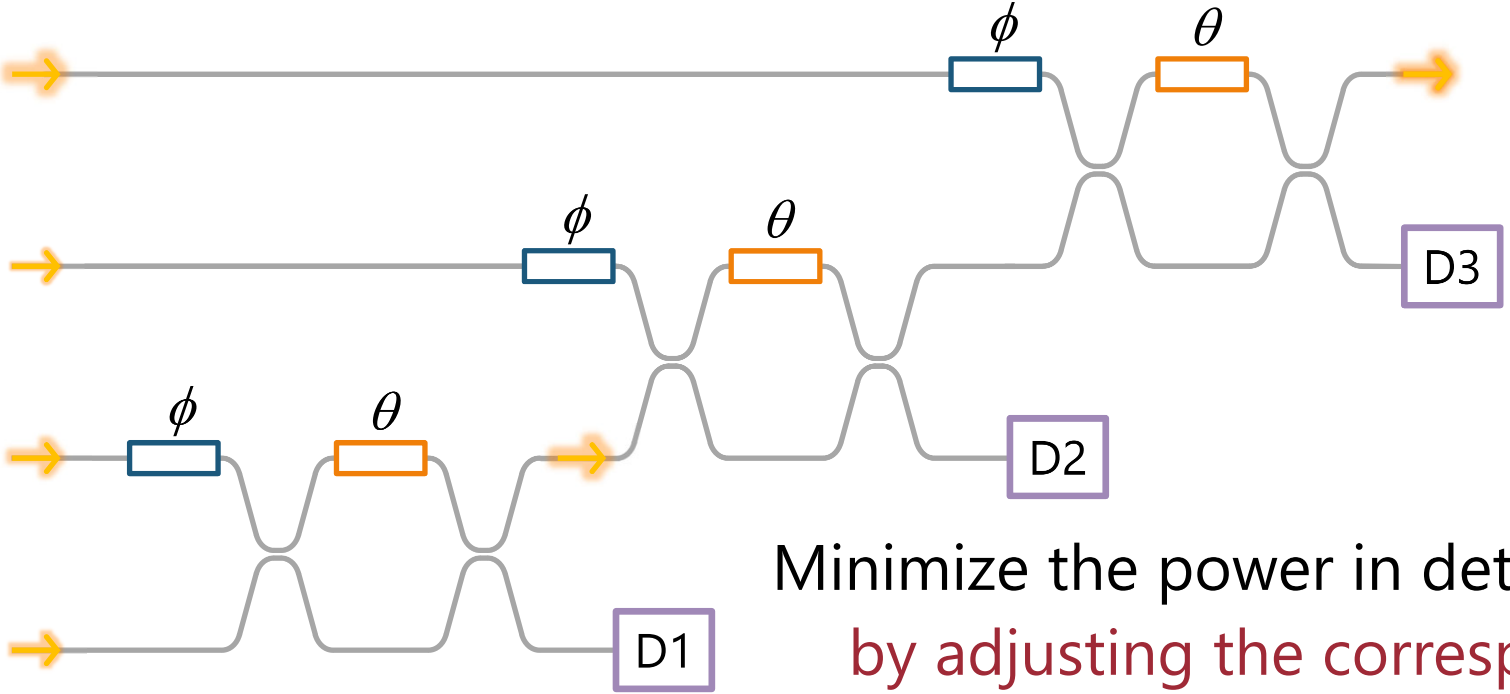
Nulling a Mach-Zehnder output

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

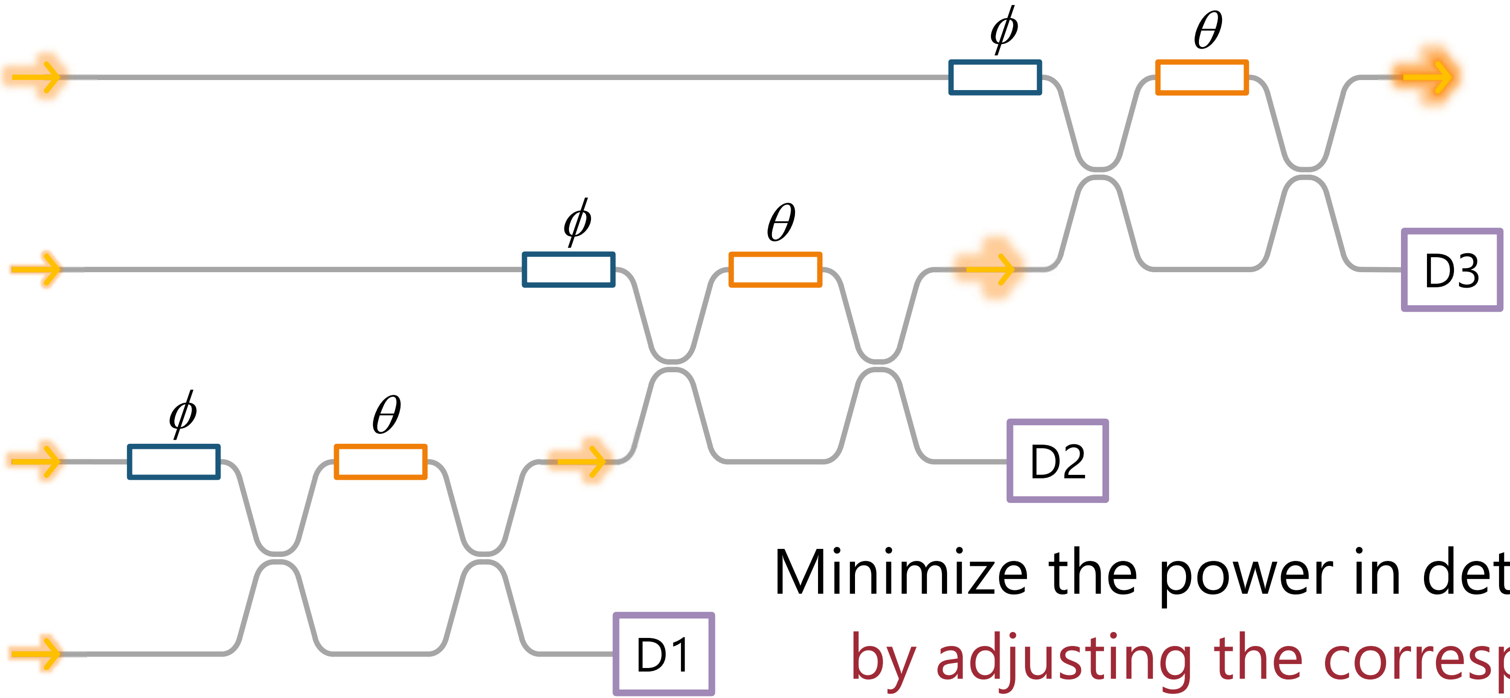
by adjusting the corresponding ϕ

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



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

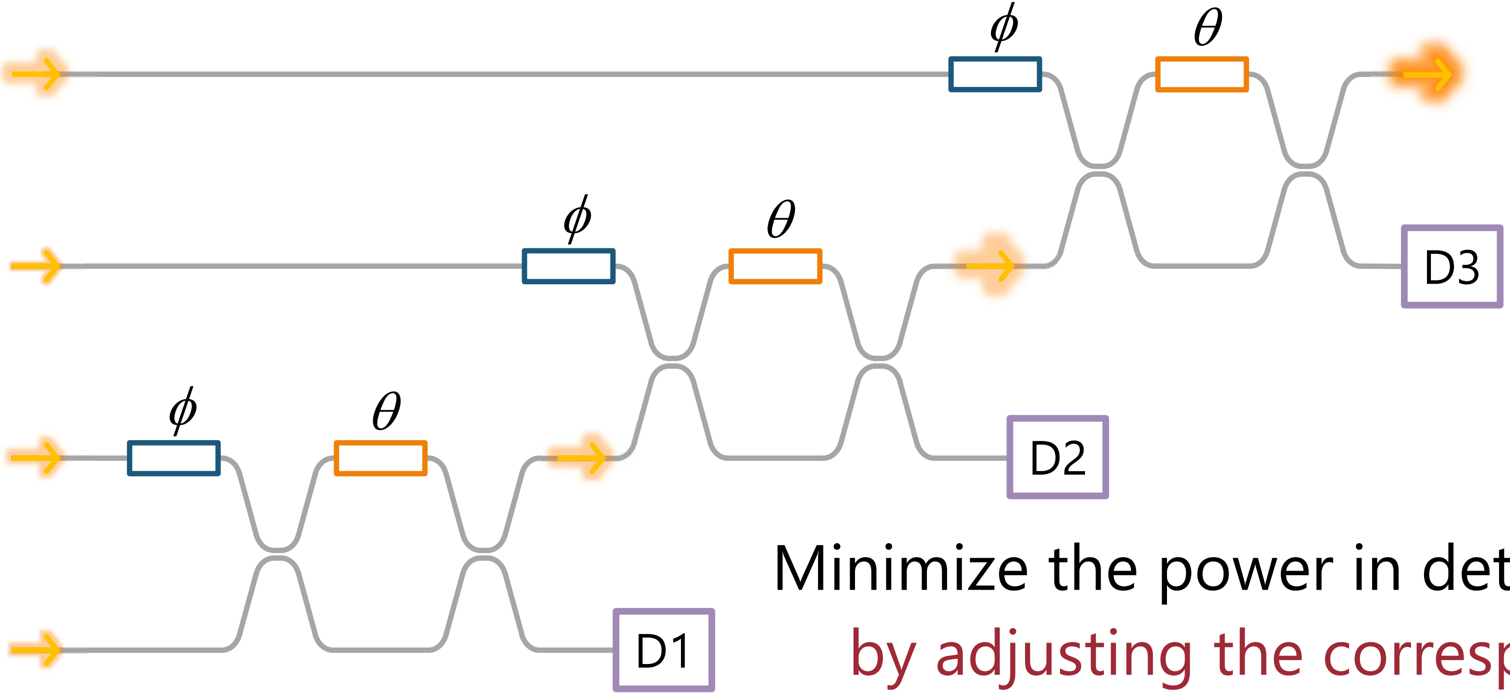
Minimize the power in detector D2

by adjusting the corresponding ϕ

and then θ

putting all power in the upper output

“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

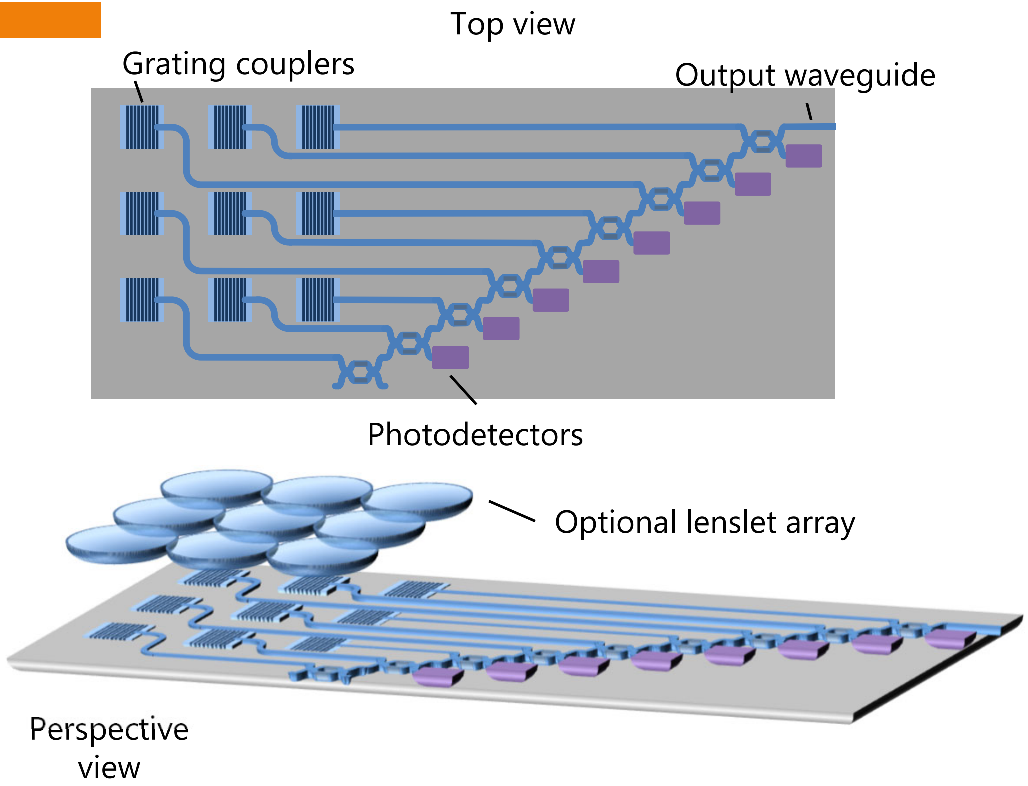
Grating couplers could couple a free-space beam to a set of waveguides

Then

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

This could run continuously

- tracking changes in the beam

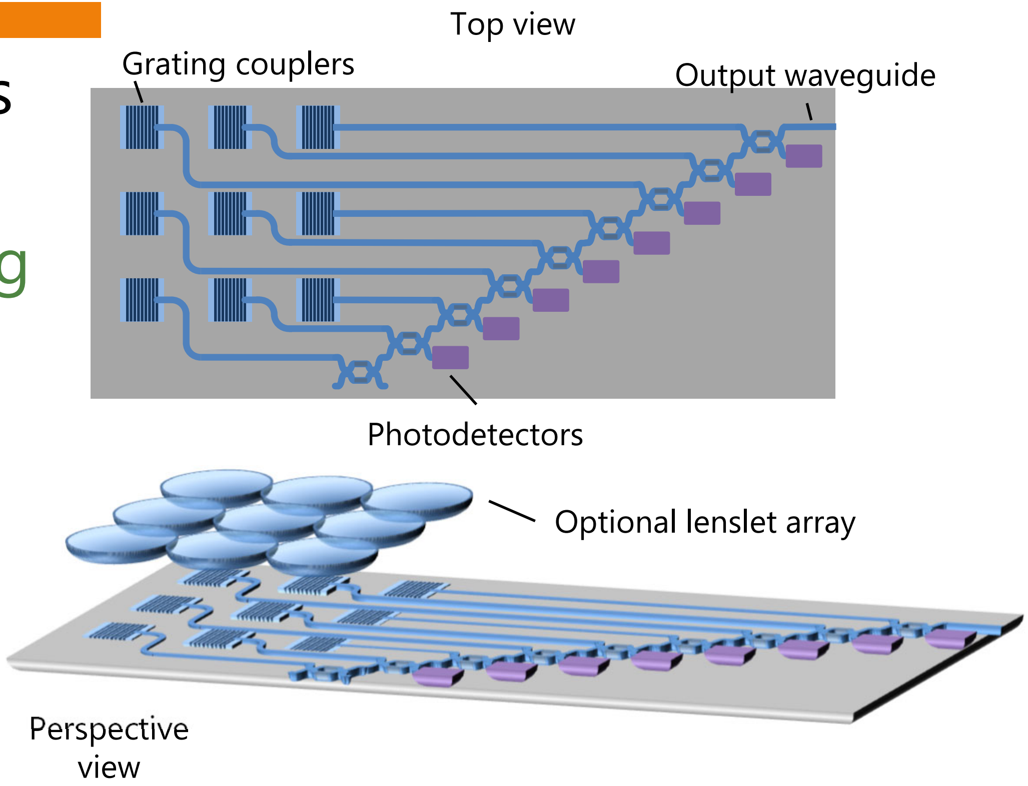


"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

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
  - …

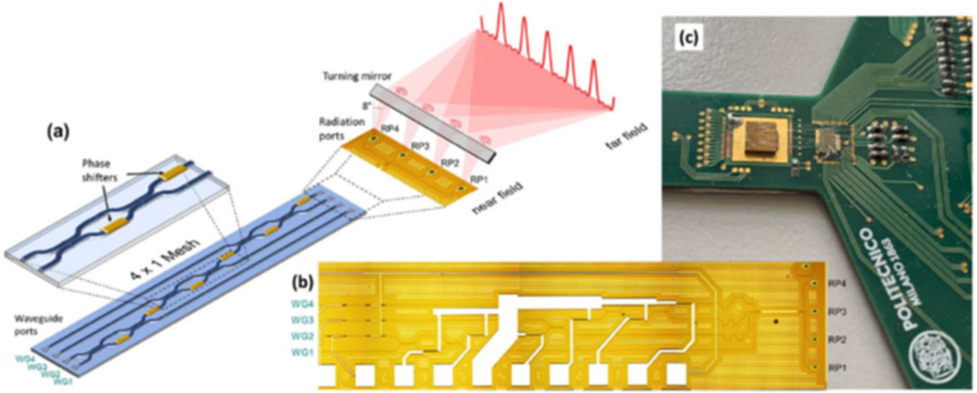


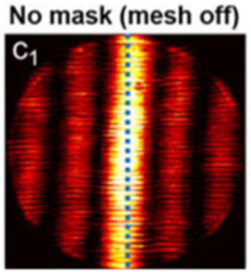
"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

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



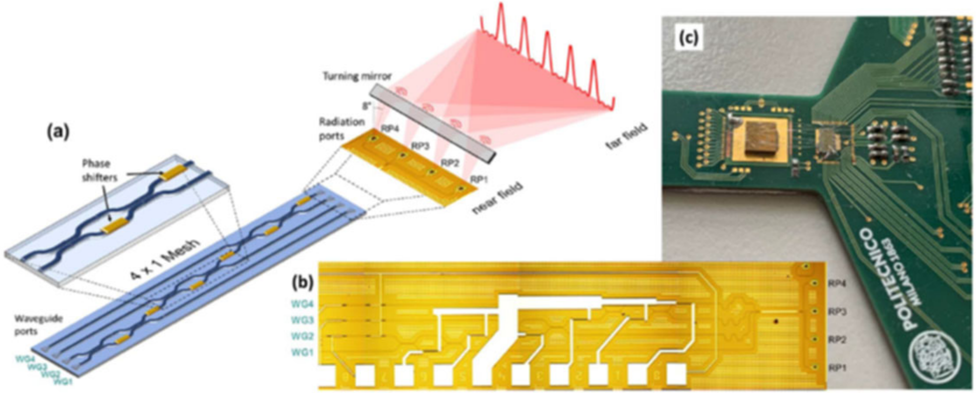


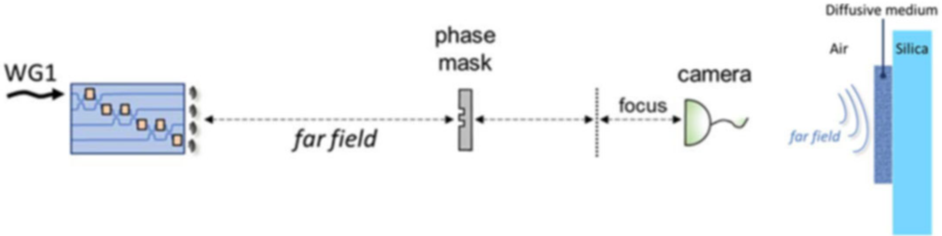
M. Milanizadeh, F. Toso, G. Ferrari, T. Jonuzi, D. A. B. Miller, A. Melloni, and F. Morichetti, "Coherent self-control of free-space optical beams with integrated silicon photonic meshes,". Photonics Research 9, 2196-2204 (2021)

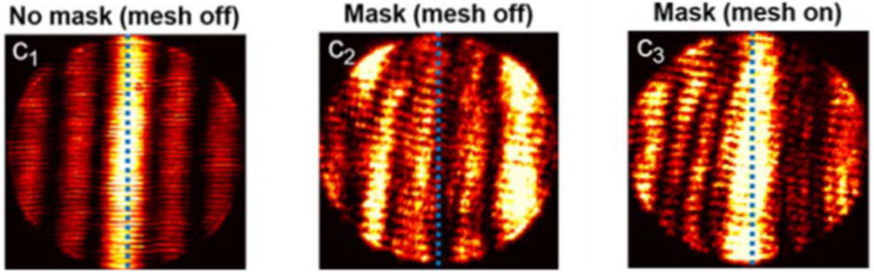
Pre-compensating a beam

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







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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

Another optimization – perfect optics from imperfect components

Perfect optics from imperfect components

But what if the Mach-Zehnder interferometers are not perfect?

- In particular
  - the split ratio in the beamsplitters may not be 50:50

Without 50:50 split ratio in the beamsplitters

- we cannot in general get perfect cancellation at the outputs
  - limiting the functionality

Optica **2**, 747-750 (2015)

Perfect optics from imperfect components

- However, there is an algorithm for adjusting the split ratios after fabrication
  - only by maximizing or minimizing power in detectors
    - to set both beamsplitters to 50:50
- If we use MZIs themselves as effective variable beamsplitters
  - the fixed, fabricated split ratios can be as bad as 85:15

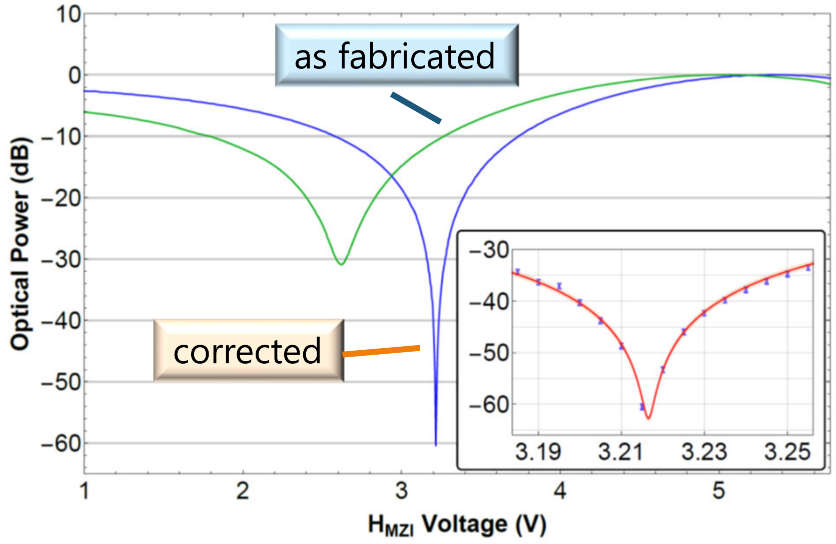
Optica **2**, 747-750 (2015)

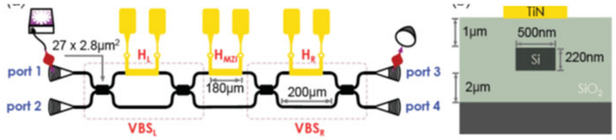
Self-correcting Mach-Zehnder

Using our algorithm to adjust the effective beamsplitter ratios
- we can improve the rejection ratio from -30 dB to -60 dB

No calibration or calculations are required

This is based only on
- power minimization or maximization
- in an output detector





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Using a self-aligning beam coupler to analyze or generate multimode fields

Analyzing multimode fields

Suppose we have a field with amplitudes in various different modes

- How do we analyze that automatically?

There are various ways to separate modes

- which could give us the relative magnitudes
  - But how would we get the relative phases?

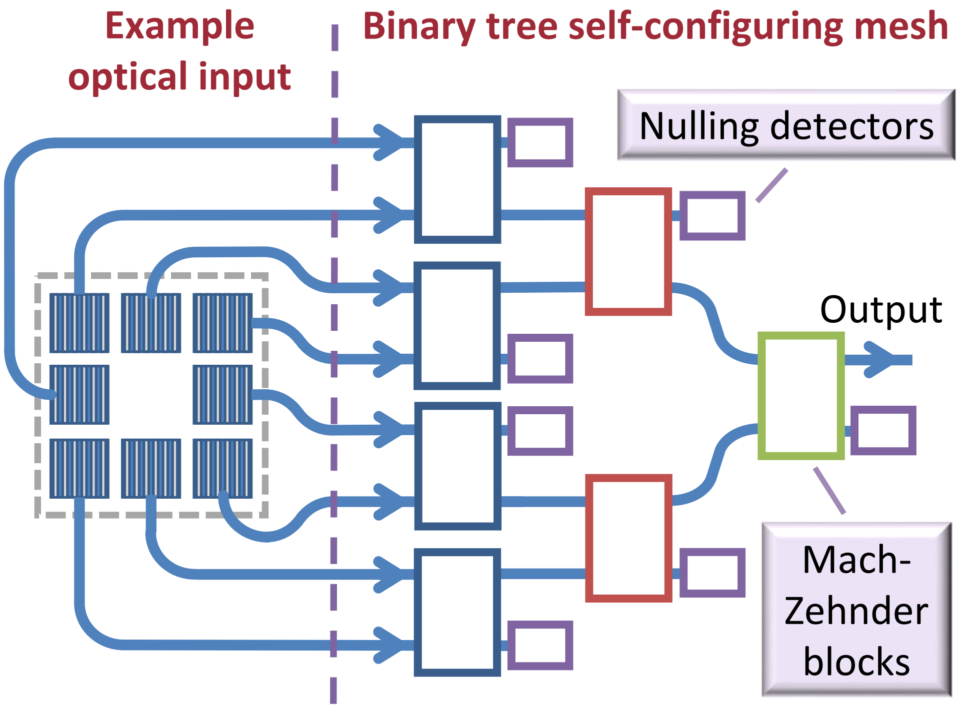
We could interfere with a coherent reference beam

- - and perform some additional calculations
- But we may not have such a beam
  - For example, if we are looking at a remote source
    - or one that is broadband or of limited coherence

Analyzing a multimode field automatically

If we shine in the beam

- and have this mesh network self-align
- then from the settings of the phase shifters in the mesh
- we can simply deduce all the relative amplitudes and phases of the inputs



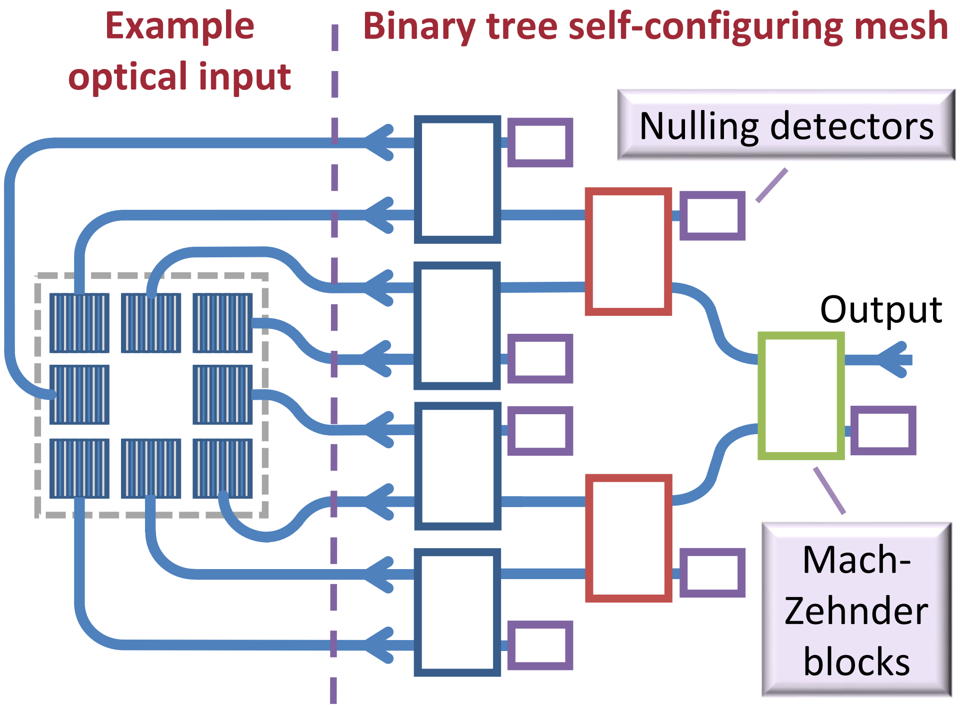
Optica **7**, 794 (2020)

Generating an arbitrary multimode field

We can also run this network in reverse

shining light backwards into the output

to controllably generate any desired multimode field backwards on the left



Optica **7**, 794 (2020)

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

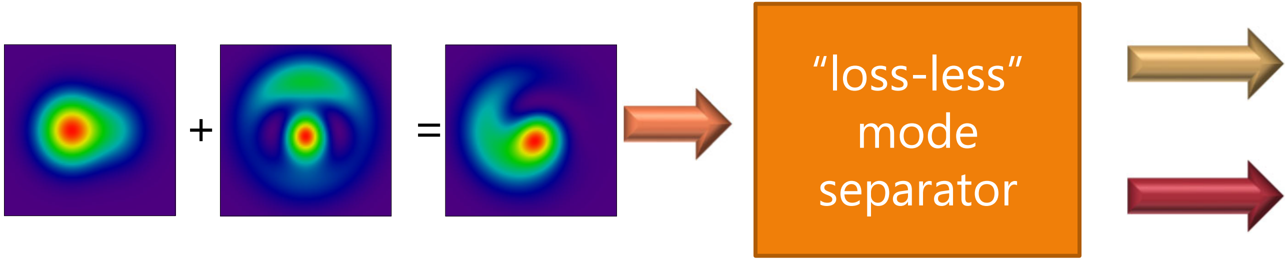
Example - Separating overlapping beams

In situations with

fixed

highly symmetric beams

there are good specific low-loss separation solutions



But for general cases

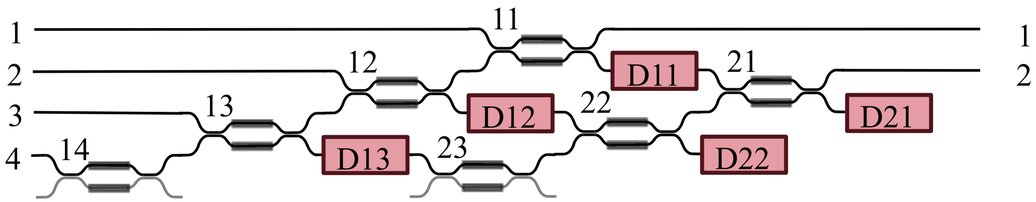
of lower symmetry and/or higher complexity

or where the beams change in time

general solutions have not been known

Separating multiple orthogonal beams

Input beam(s) (sampled into waveguides)



Output 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"

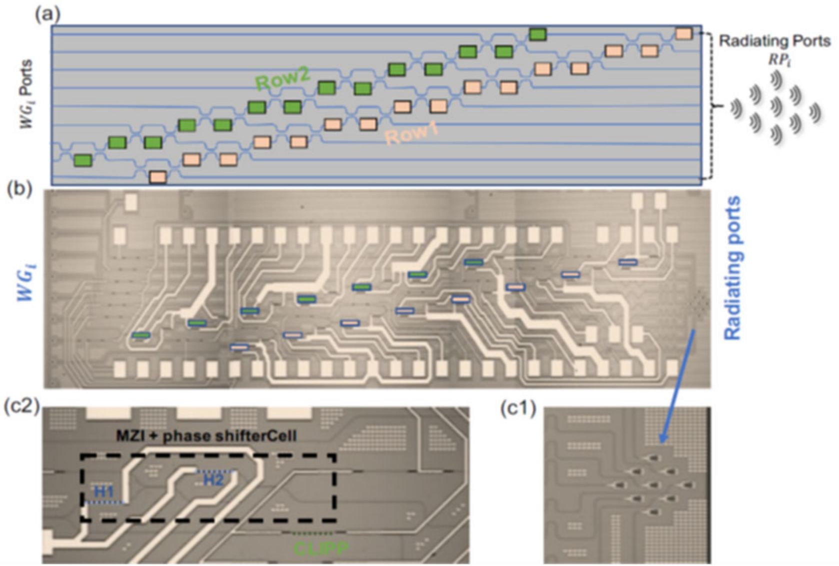
where we self-align it to output 2 using detectors D21 – D22

separating two overlapping orthogonal beams to separate outputs

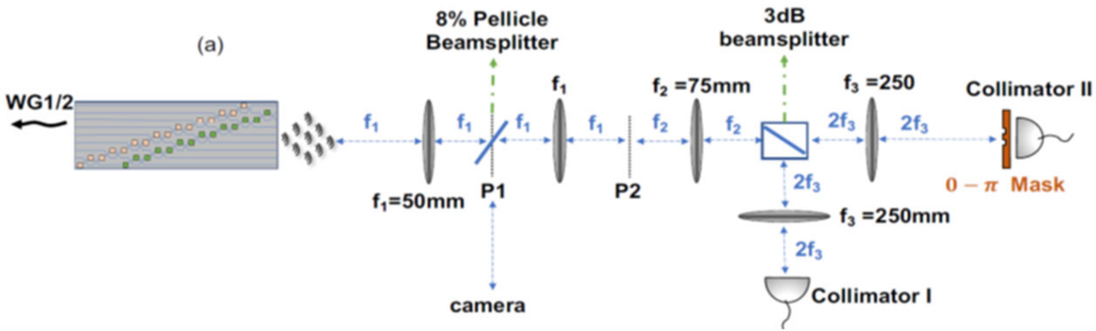
Separating free-space modes

9x2 diagonal line mesh

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

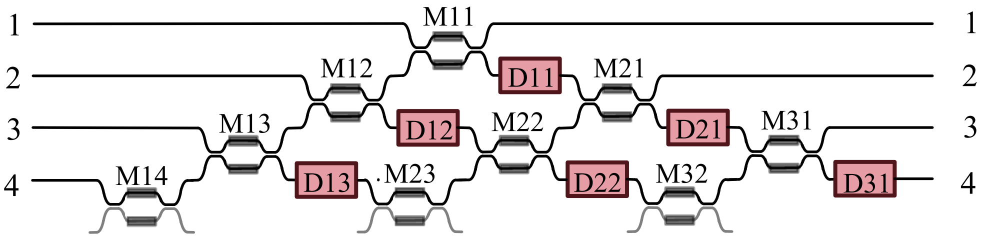


Maziyar Milanizadeh, SeyedMohammad SeyedinNavadeh, Francesco Zanetto, Vittorio Grimaldi, Christian De Vita, Charalambos Klitis, Marc Sorel, Giorgio Ferrari, David A. B. Miller, Andrea Melloni, and Francesco Morichetti, "Multibeam Free Space Optics Receiver Enabled by a Programmable Photonic Mesh," https://arxiv.org/ftp/arxiv/papers/2112/2112.13644.pdf



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

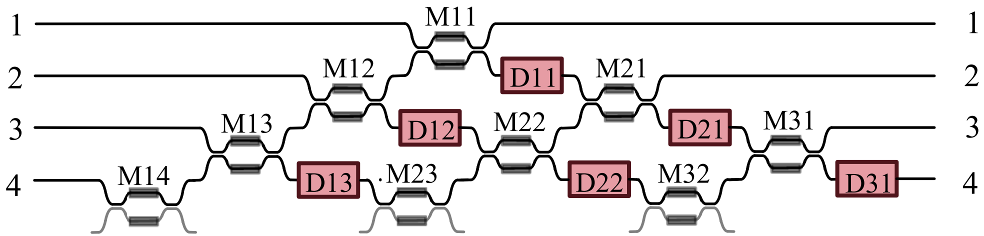
separates a number of orthogonal beams

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"

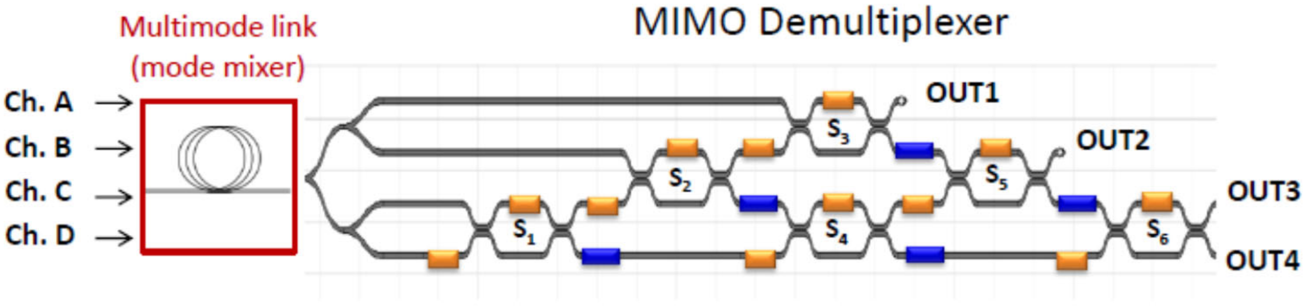
and have the corresponding diagonal row of detectors look for that tone

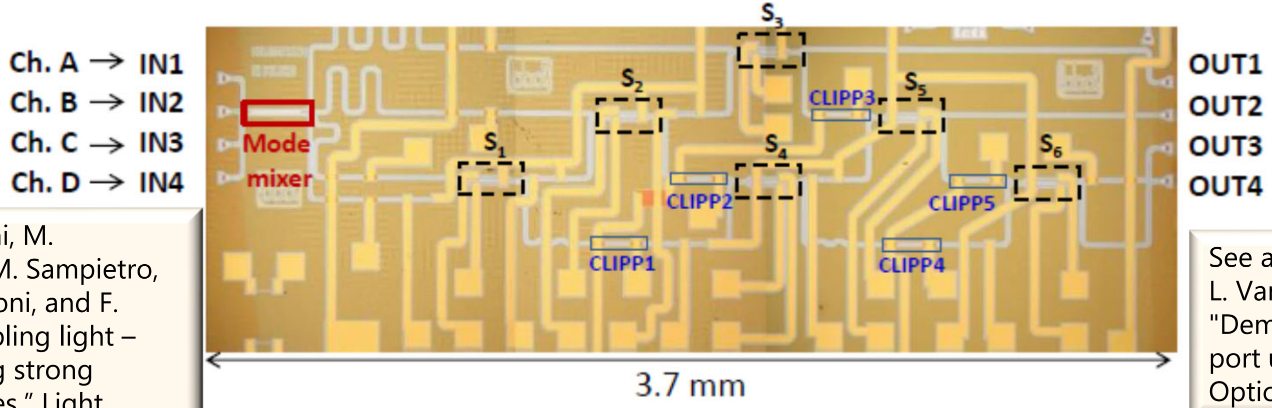
then the mesh can continually adapt to the orthogonal inputs

even when they are all present at the same time

and even if they change

Integrated MIMO demultiplexer: technology





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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

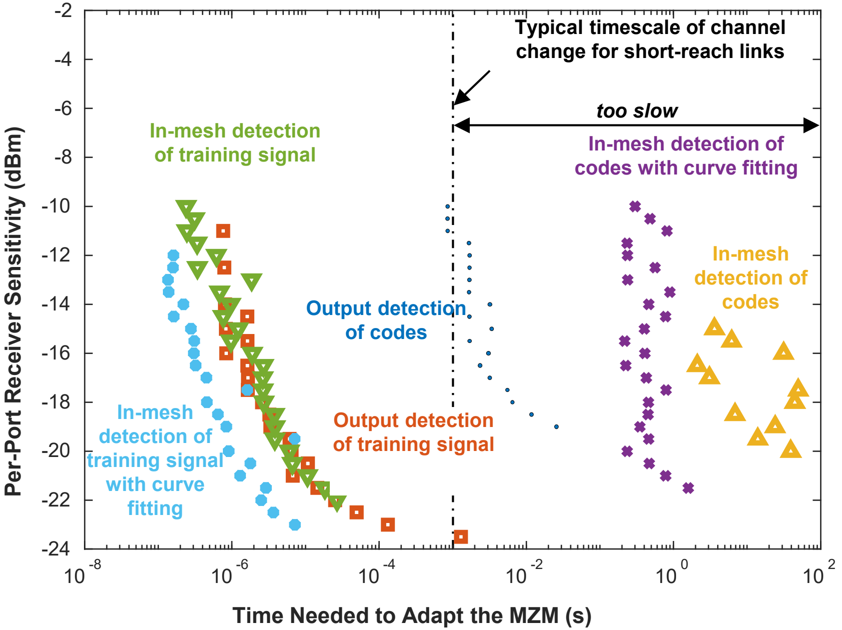
comparing several minor variants of the detection approach

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

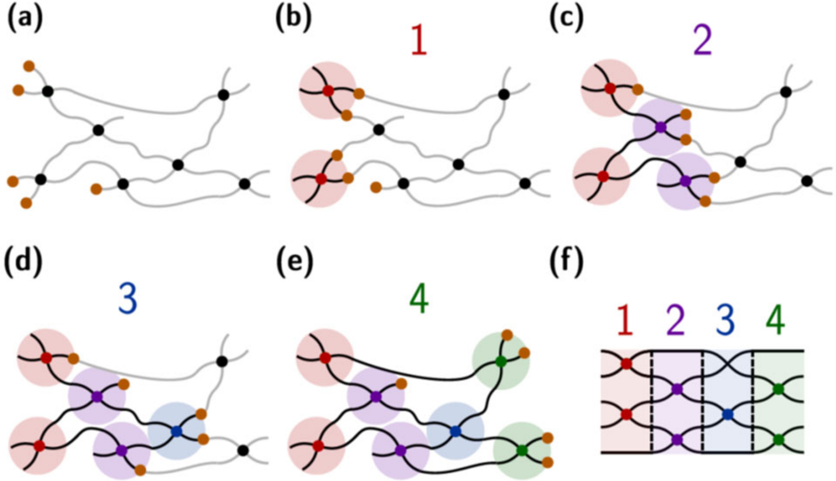
Different mathematical concepts

such as graph theory

are starting to appear in discussions of optics

e.g., directed acyclic graphs

which correspond to "forward-only" circuits



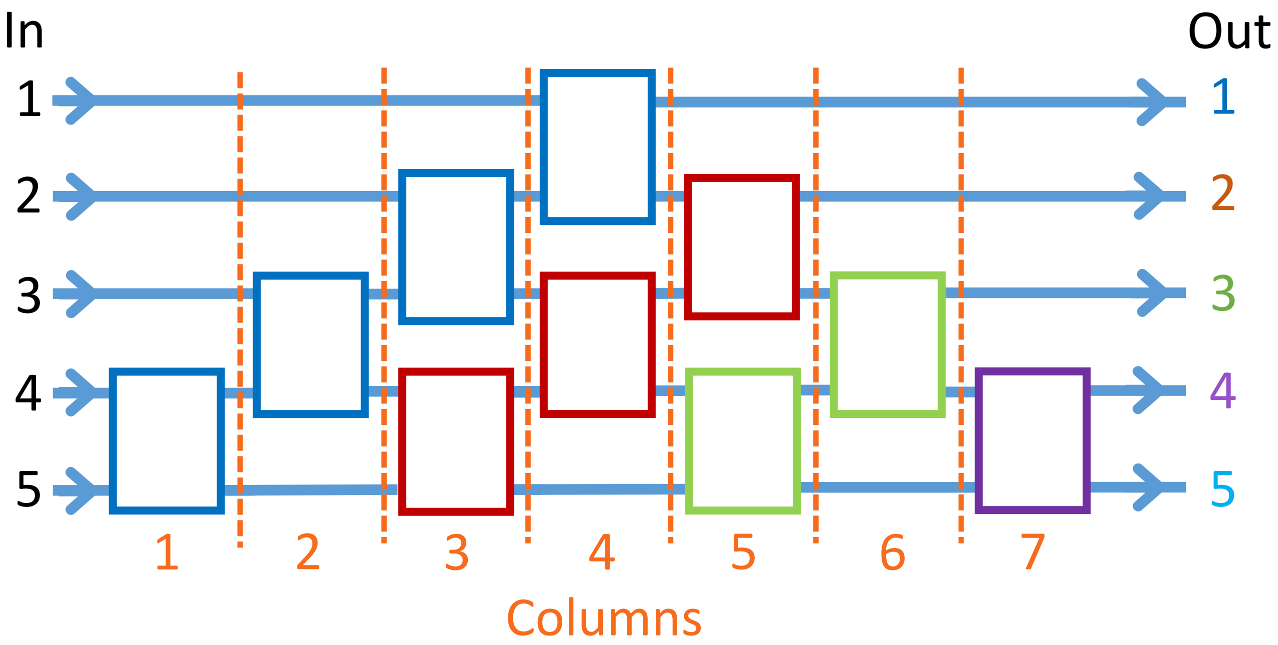
Topological sorting of an optical network into columns for parallel configuration

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

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

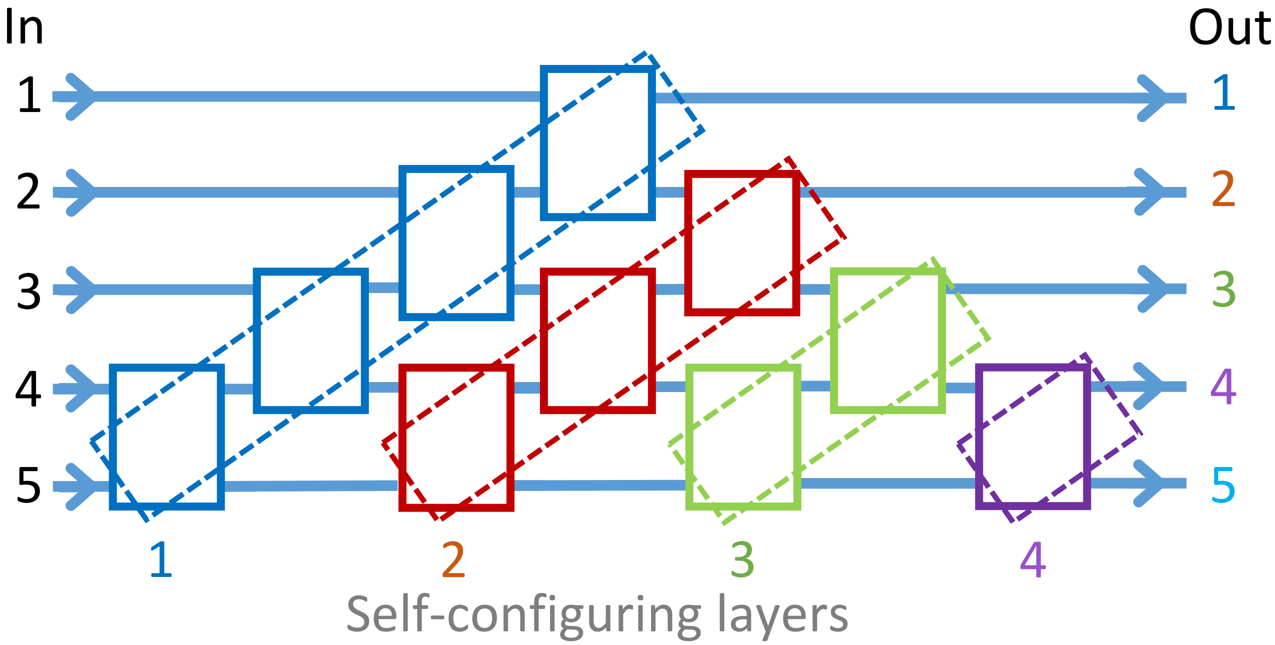
Column topology

"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

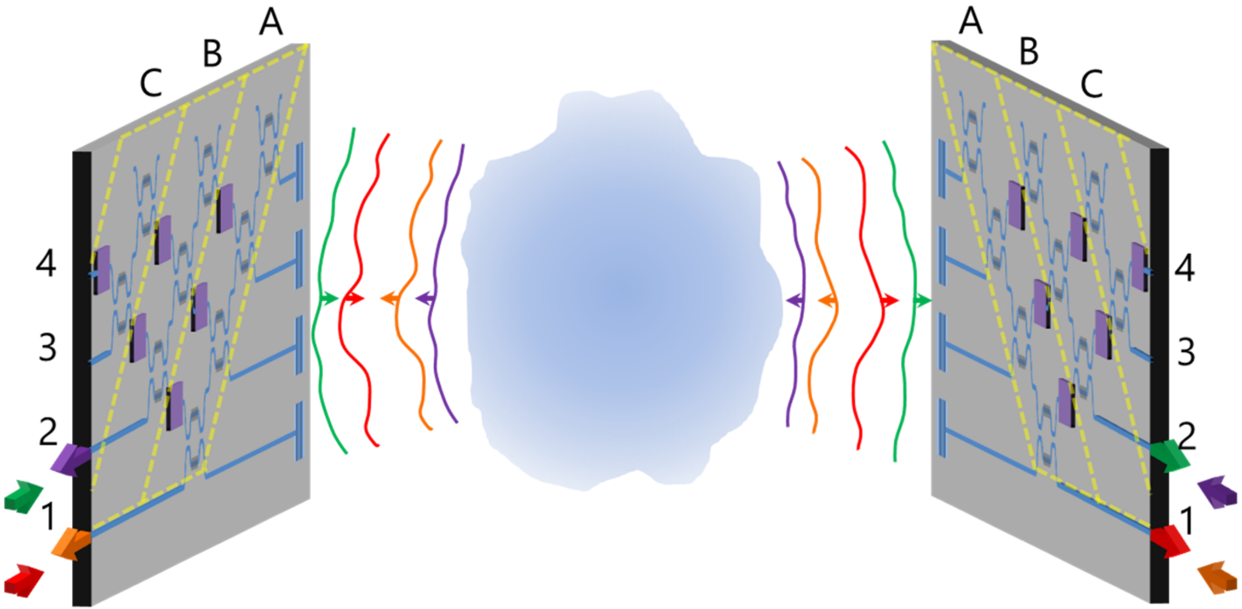
  e.g., for undoing atmospheric turbulence or mode scattering in fibers
- finding the best channels for communications
- self-calibrating, self-correcting and self-stabilizing complex optical systems

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

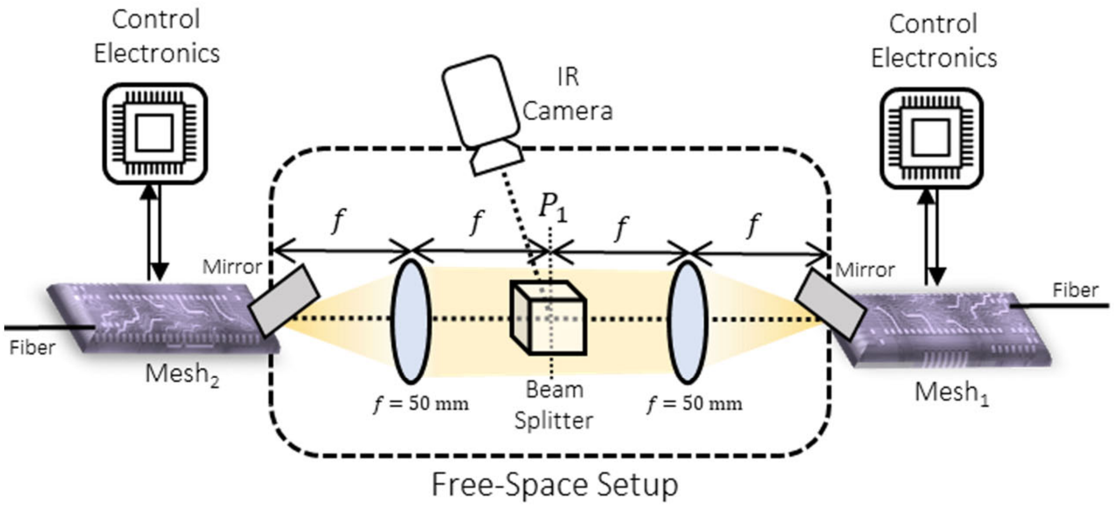
and we can introduce

aberrations or

partial blocking

in the path

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

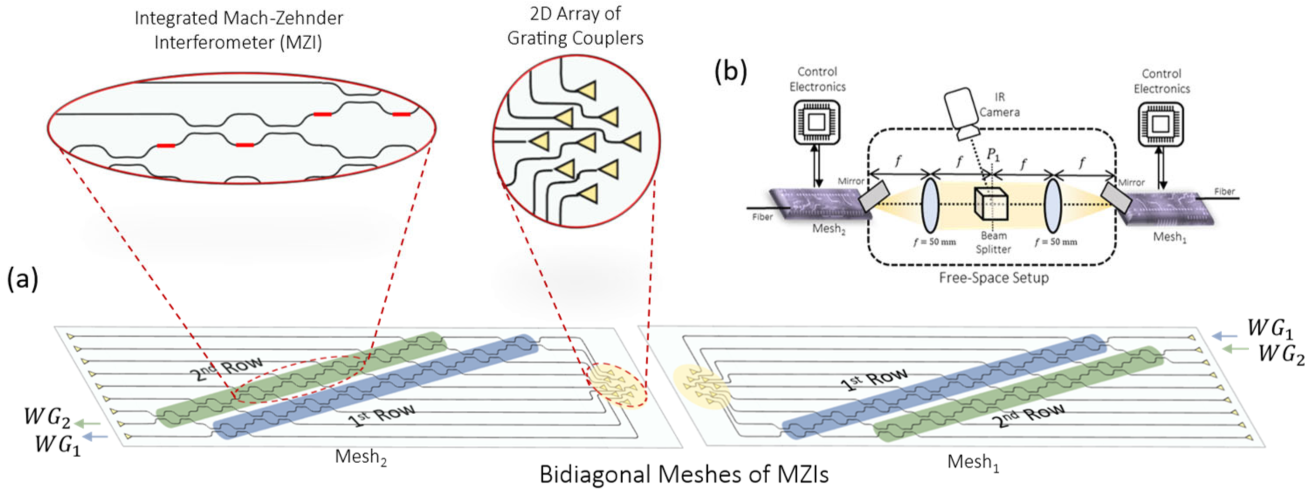


SMohammad SeyedinNavadeh, M Milanizadeh, F Zanetto, V Grimaldi, C De Vita, G Ferrari, D A B Miller, A Melloni, F. Morichetti, "Multi-channel free-space optical communication between self-configuring silicon photonics meshes", ECIO22, 4-6 May 2022, Milan, Italy, Paper F.E.2

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



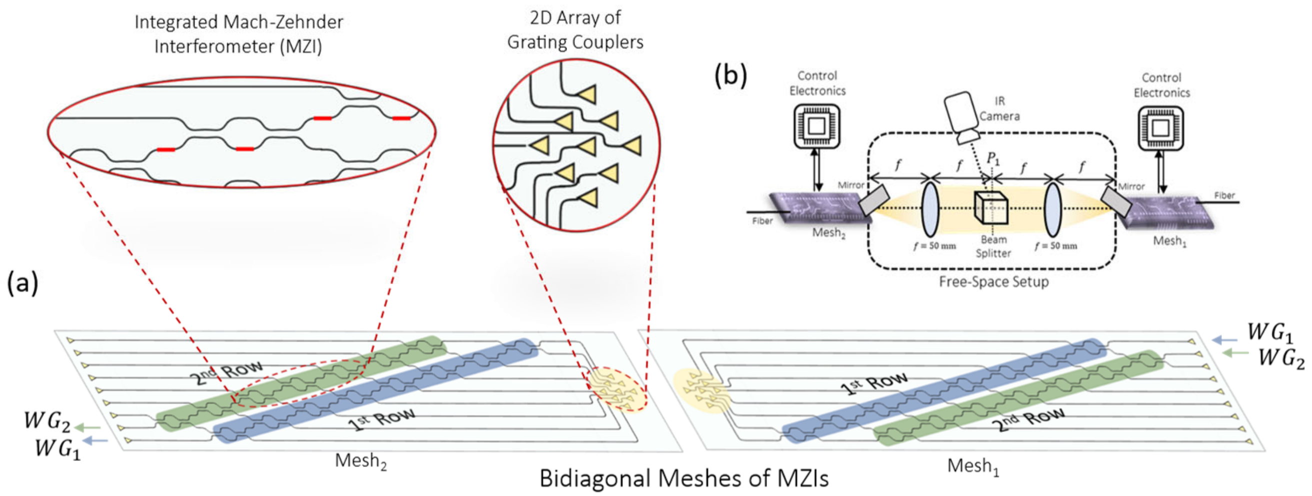
SM SeyedinNavadeh et al., ECIO22, Paper F.E.2

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

Other applications and extensions

- arbitrary linear transforms and matrix multiplications
- 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

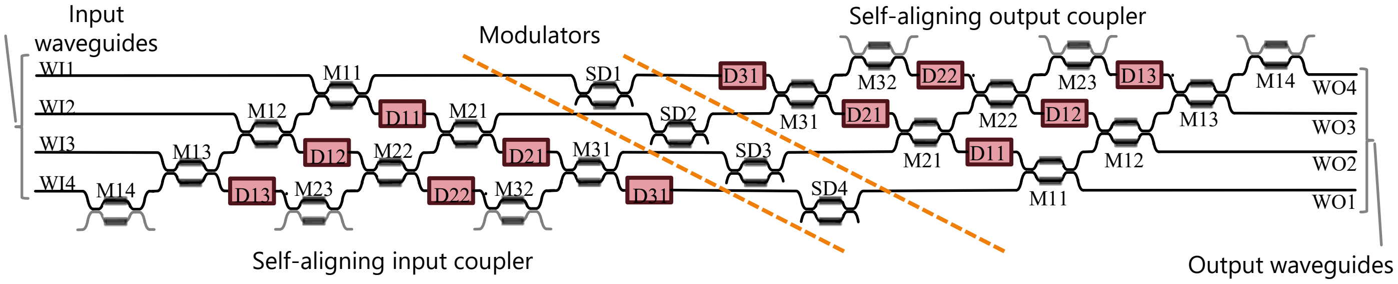
Universal self-configuing architectures

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

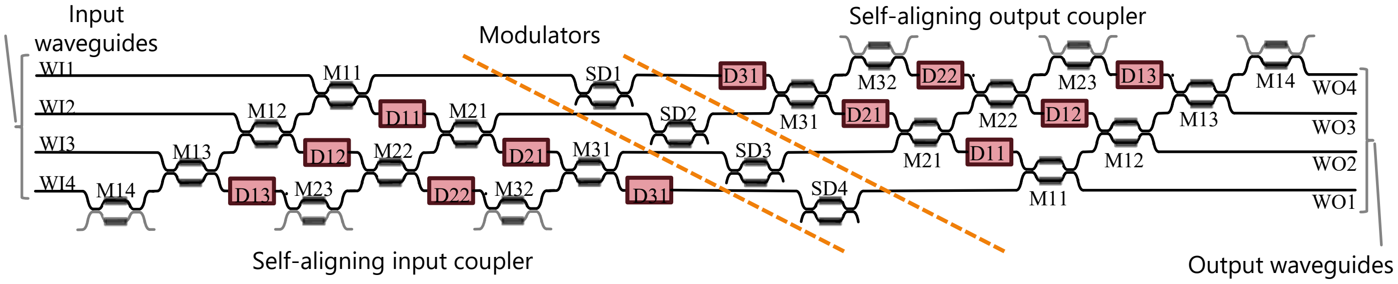
each to different single waveguides in the middle

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)

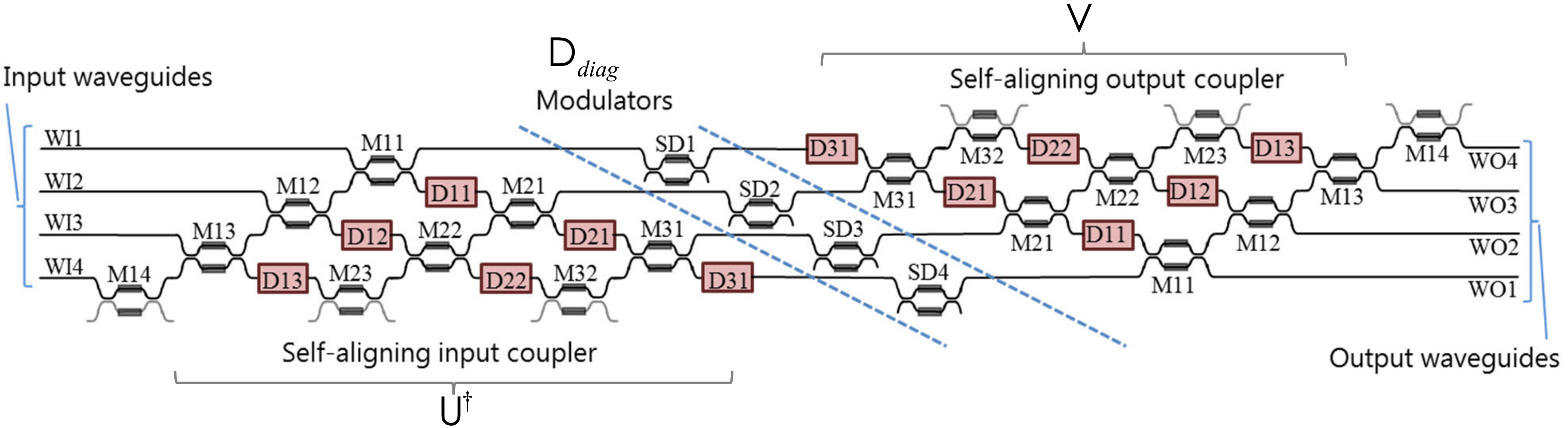
This kind of universal mode conversion, with such modulation

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

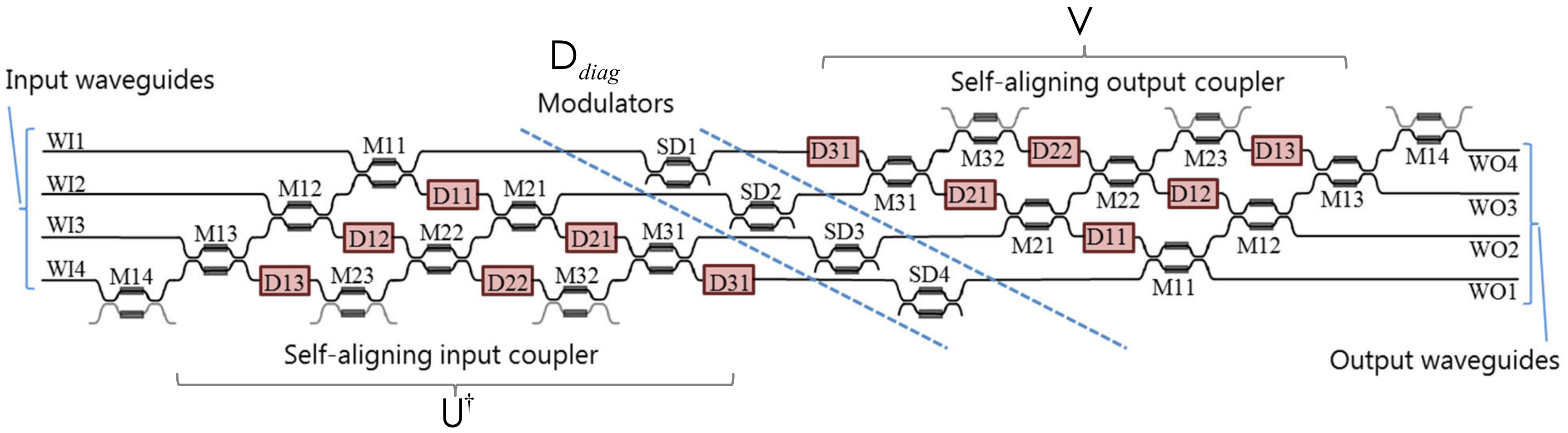
$$D = VD_{diag}U^{\dagger}$$

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

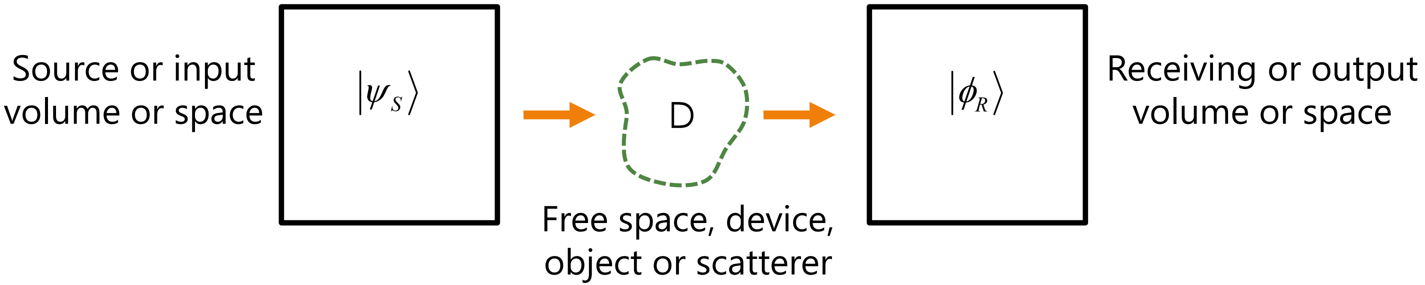
Opt. Express **20**, 23985 (2012)

- These sets of modes turn out to have basic physical significance

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

Mode-converter basis sets

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



When we think of how a source function $|\psi_S\rangle$ in a source space

gives rise to a received wave $|\phi_R\rangle$ in a receiving space

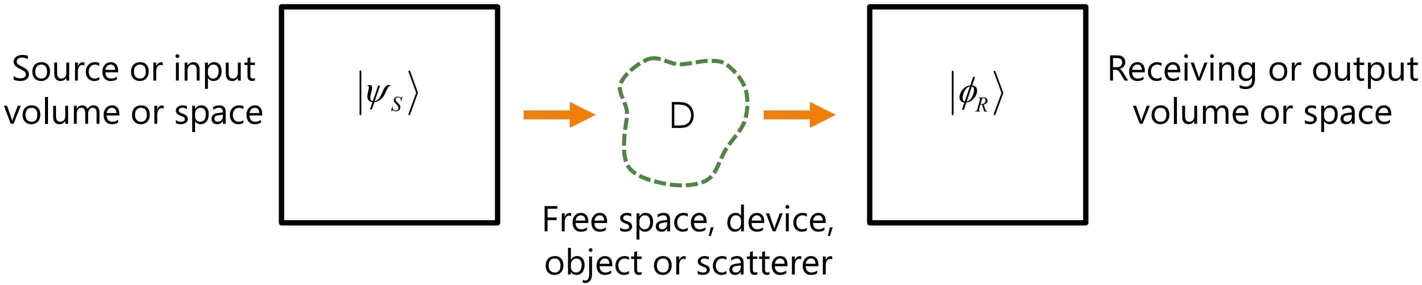
for free-space communications, or for any scatterer, optical device, or object between the spaces

there is just some linear operator D that relates the two

so, mathematically, $|\phi_R\rangle = \mathrm{D}|\psi_S\rangle$

Mode-converter basis sets

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



Because we can perform the singular value decomposition (SVD) of any linear operator D

we have what we can call

the **mode-converter basis sets** of functions

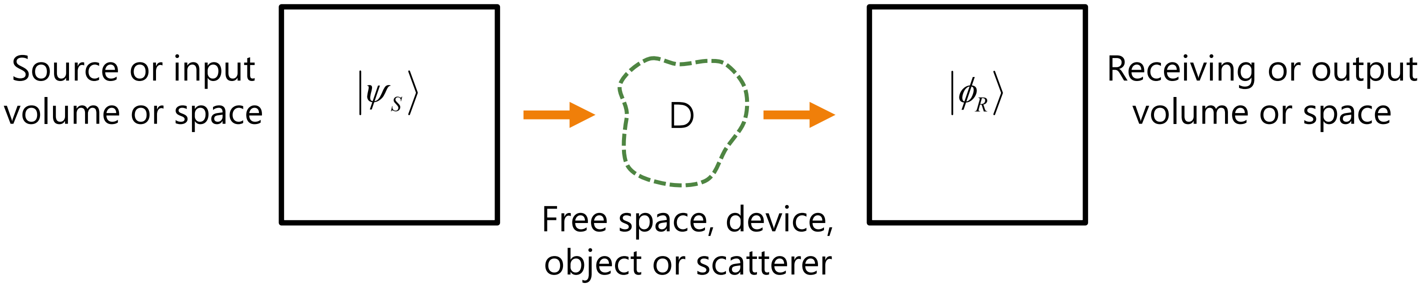
a set of orthogonal source functions $|\psi_{Sj}\rangle$

that lead, one by one

to a set of corresponding orthogonal received waves $|\phi_{Rj}\rangle$

"All linear optical devices are mode converters," Opt. Express **20**, 23985 (2012)

Mode-converter basis sets



In turn, that means that

there is a set of orthogonal channels

for communication through space

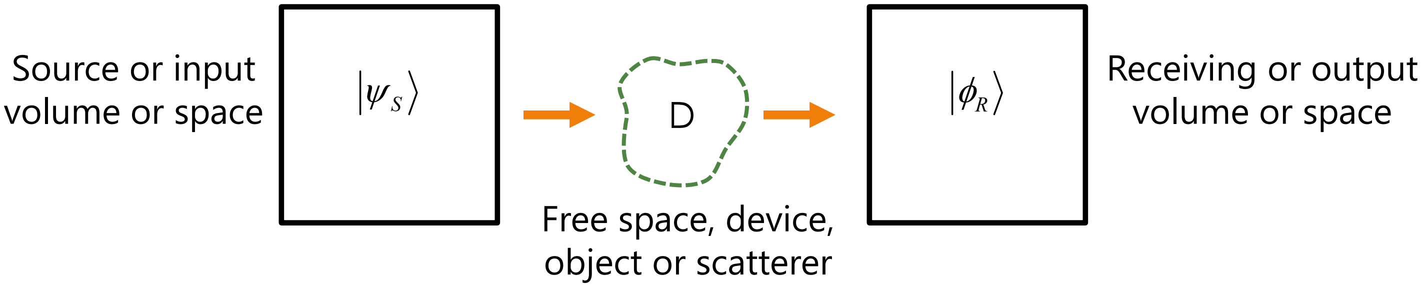
or through any linear scatterer or device

which are given by these mode-converter input and output function pairs

These are the unique and best possible choices

Communication modes

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



When we are interested in the communications through the system

we can also describe these same sets of functions as the

"communication modes"

"Communicating with Waves Between Volumes ... ," Appl. Opt. 39, 1681 (2000)

the unique set of orthogonal channels for communicating between the source and the receiver

These "modes" are the sets of source and receiving functions

not the "beams" between the spaces

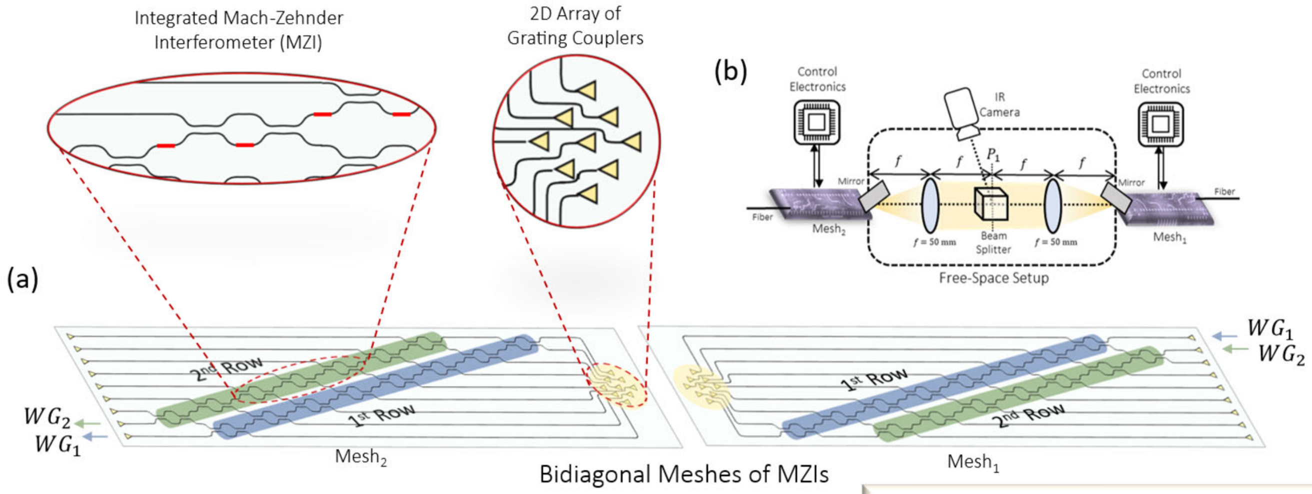
Establishing optimum orthogonal channels - experiment

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

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

Funding from Air Force Office of Scientific Research FA9550-17-1-0002

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