Self-configuring complex photonic circuits

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Self-configuring silicon photonics

Specific architectures

- can correct, stabilize, and configure themselves
  - using simple progressive algorithms
    - with local single-parameter feedback loops
  - and can adapt to the problem
    - in real time

Applications

These meshes give optical systems
  that are universal in a way that is
   beyond previous optics

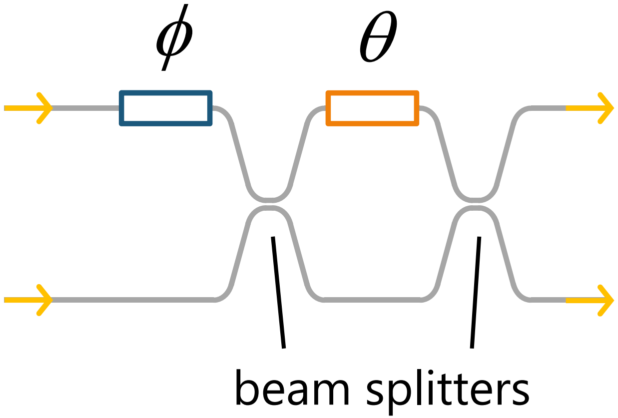
They open new opportunities in
- sensing
- communications
- and information processing, e.g.,
  - neural networks
  - solving equations

in both classical and quantum systems

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”

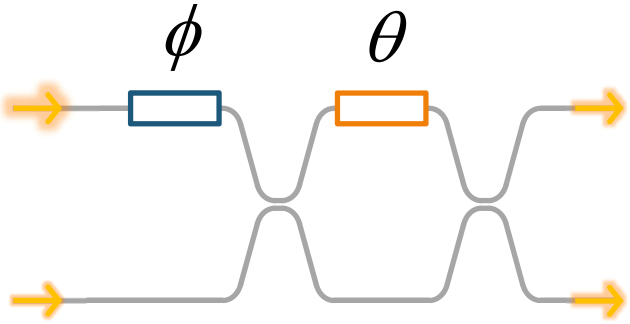


Nulling a Mach-Zehnder output

Suppose we shine (mutually coherent) light

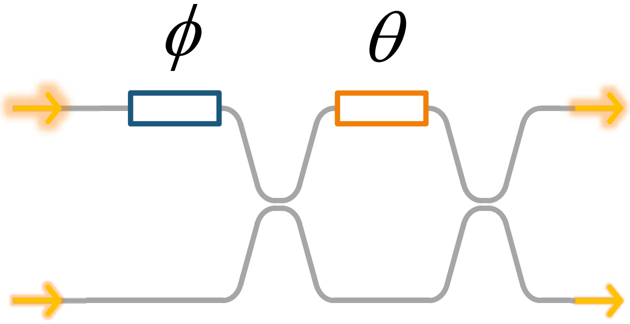
- into both interferometer inputs
  - with possibly different amplitudes and phases

We can adjust ϕ to minimize the power at, say, the bottom output



Nulling a Mach-Zehnder output

- Suppose we shine (mutually coherent) light
  - into both interferometer inputs
    - with possibly different amplitudes and phases
- We can adjust ϕ to minimize the power at, say, the bottom output
  - The fields from the two inputs
    - are now in "antiphase" at the bottom output



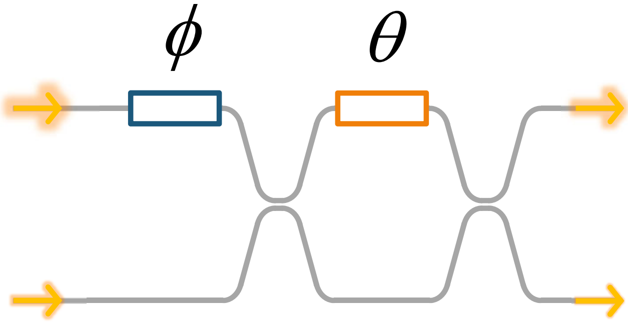
Nulling a Mach-Zehnder output

Adjusting θ

- sets the "split ratio" of the MZI
  - that is, how the power from one input would be split between the outputs

Interestingly, for 50:50 beamsplitters

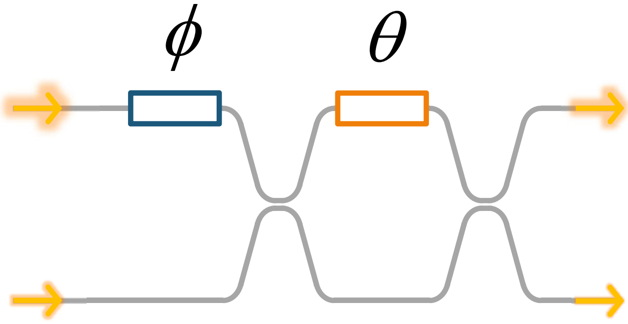
- adjusting θ does *not* change the relative phase with which the two inputs mix at an output
  - That is controlled *only* by ϕ



Nulling a Mach-Zehnder output

So, since we have already minimized the bottom output power by adjusting ϕ

- if we now adjust θ
  - we will be able to minimize that power to zero
    - because the contributions from the two inputs
      - are already in antiphase at the bottom output



Nulling a Mach-Zehnder output

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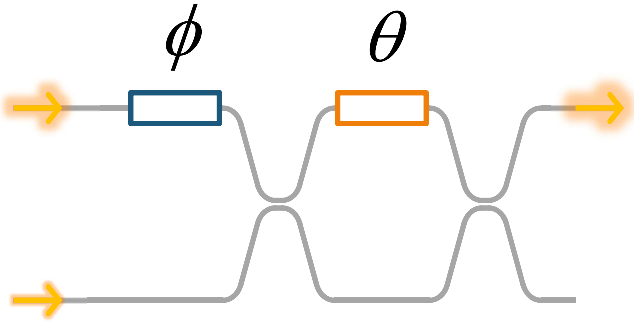
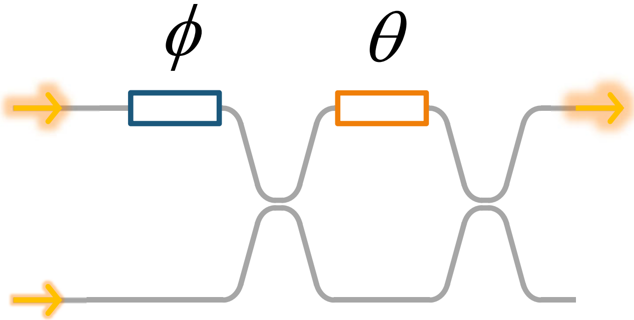


Nulling a Mach-Zehnder output

So, in an MZI with 50:50 beamsplitters

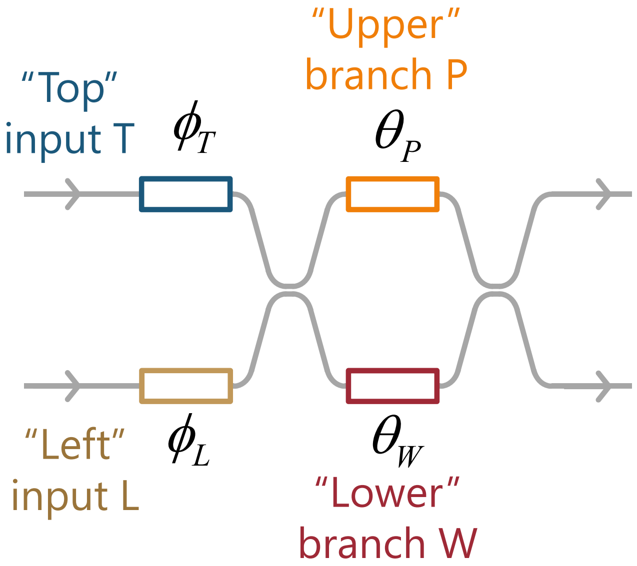
- for any relative input amplitudes and phases
  - we can "null" out the power at the bottom output
    - by two successive single-parameter power minimizations
      - first, using ϕ
      - second, using θ



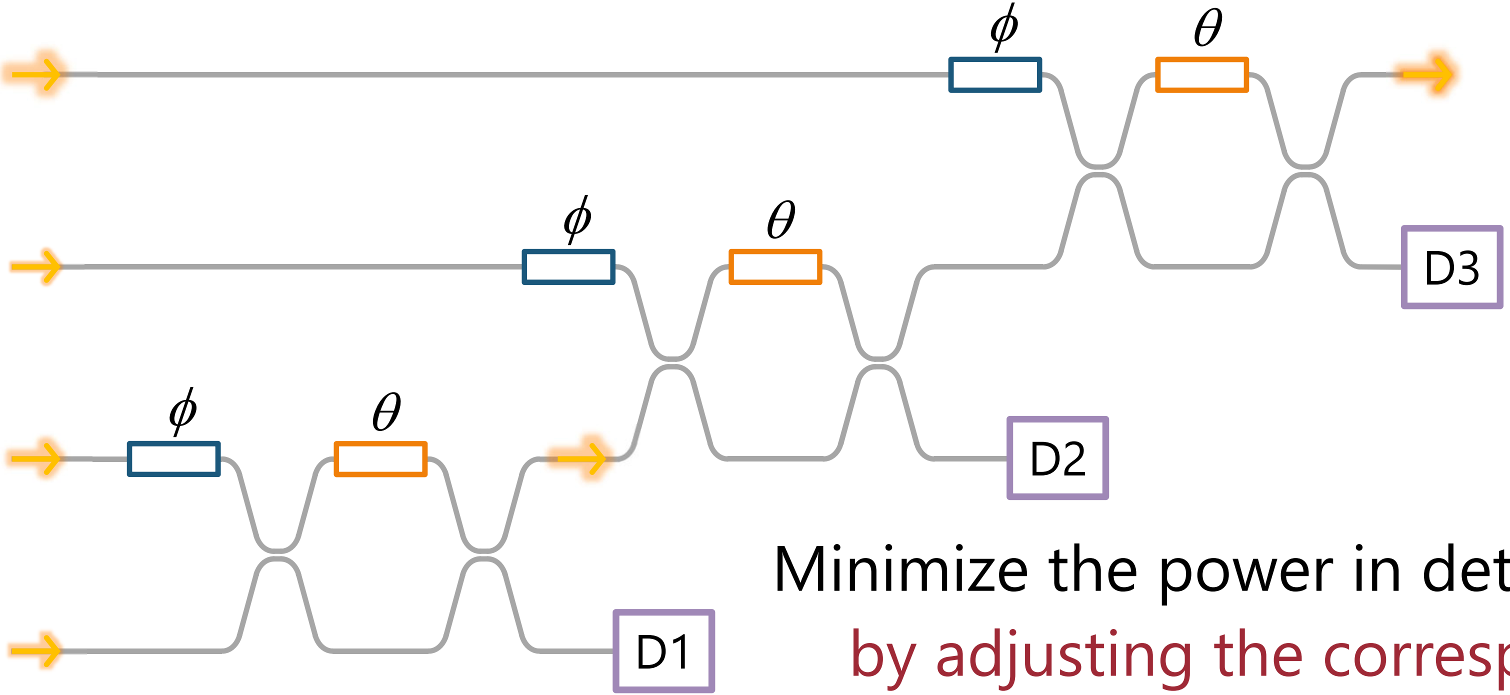
Nulling a Mach-Zehnder output

In fact

- in making meshes of MZIs
  - we can use MZI blocks with phase shifters
    - in any two of these four locations
      - as long as at least one phase shifter is on an interferometer arm



“Diagonal line” self-aligning coupler



Minimize the power in detector D1

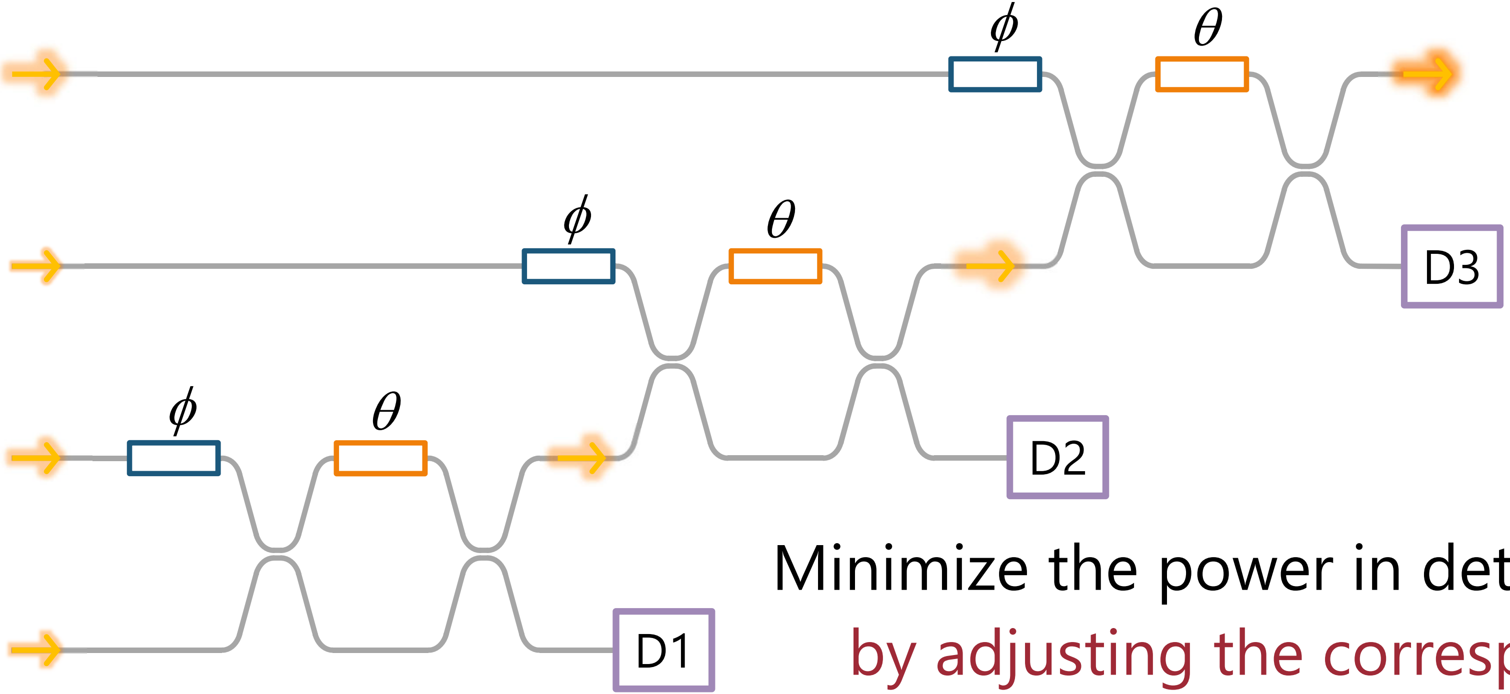
by adjusting the corresponding ϕ

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

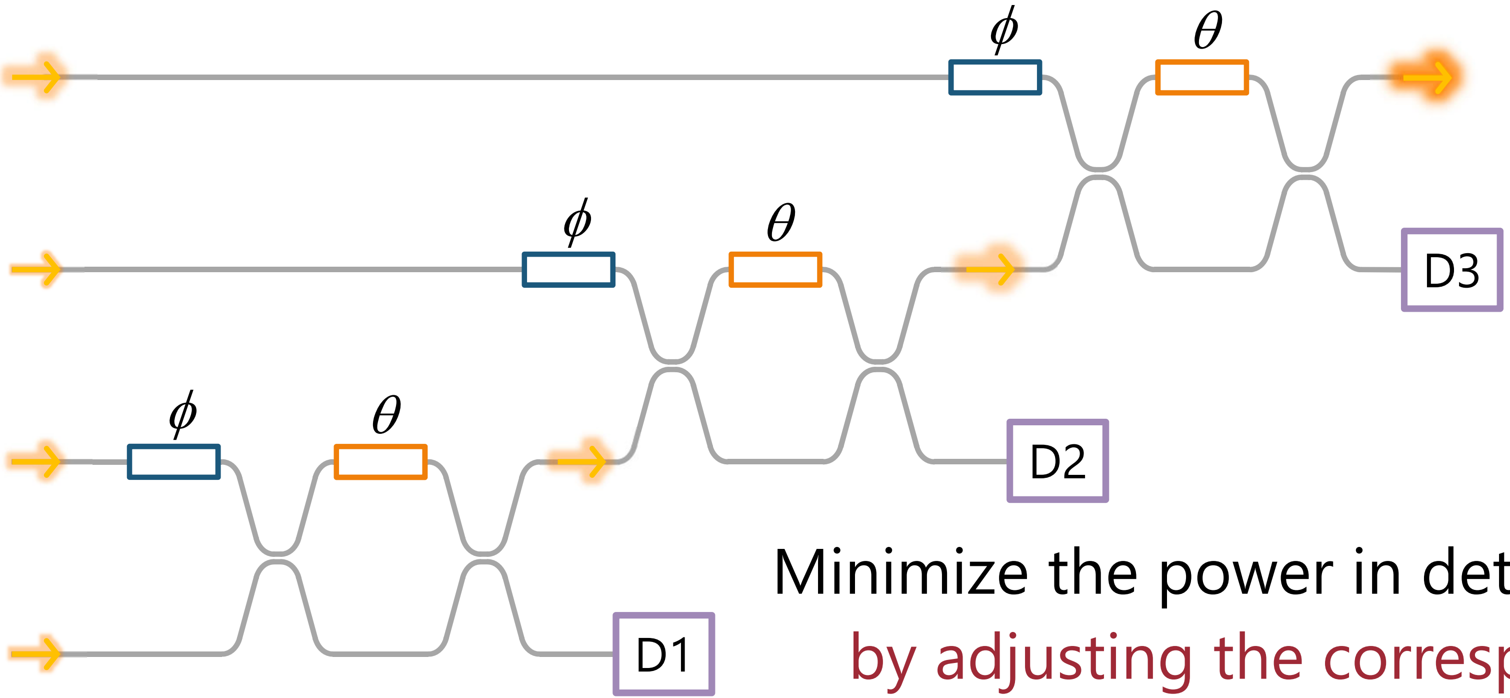
by adjusting the corresponding ϕ

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

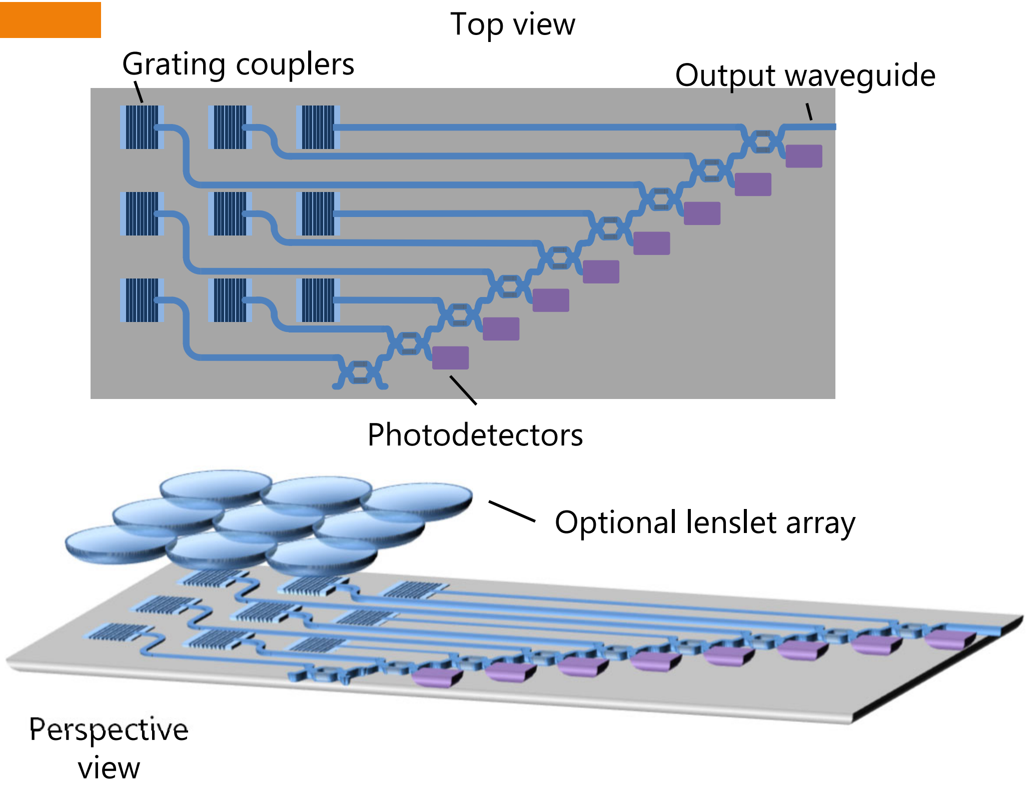
and then θ

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

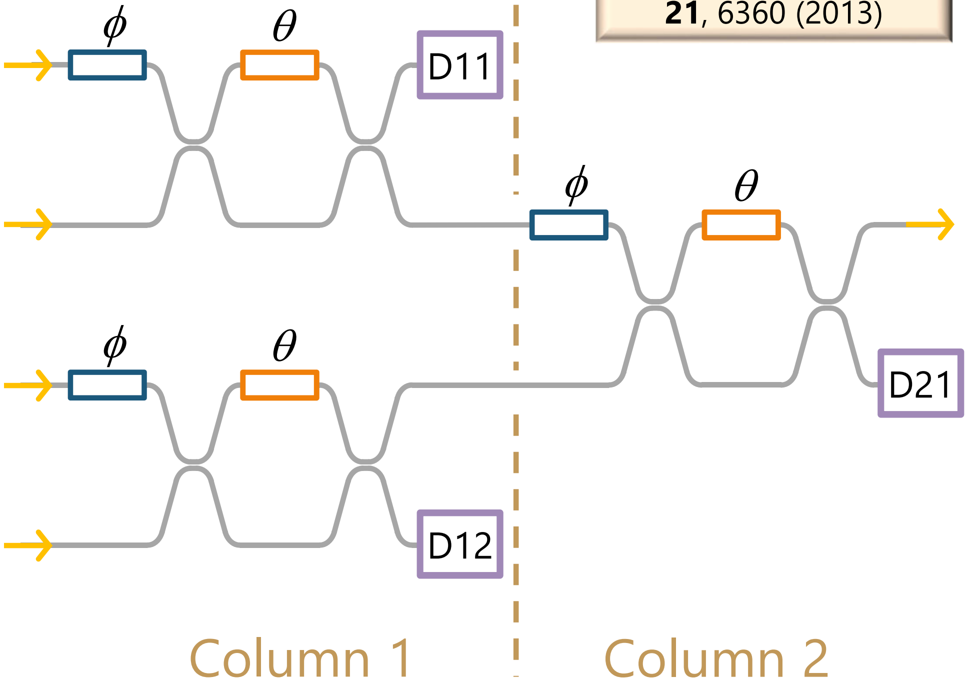


“Self-aligning universal beam coupler,” Opt. Express **21**, 6360 (2013)

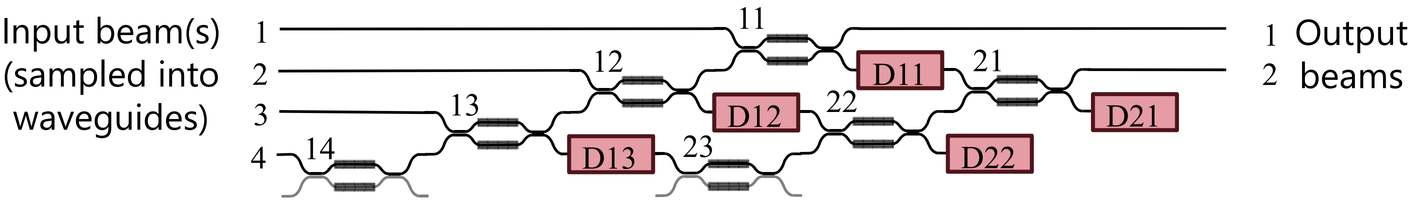
Binary tree self-aligning coupler

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

- A “binary tree” also supports self-alignment
  - It uses same number of MZIs in each path
    - and is the “shortest” possible self-aligning coupler mesh
- Each “column” of MZIs can be optimized in parallel
  - allowing faster self-configuration



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

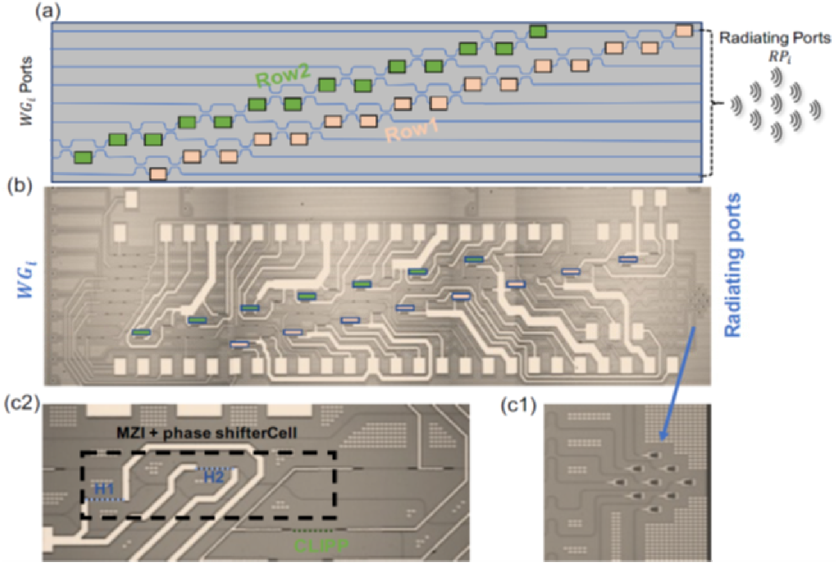
separating two overlapping orthogonal beams to separate outputs

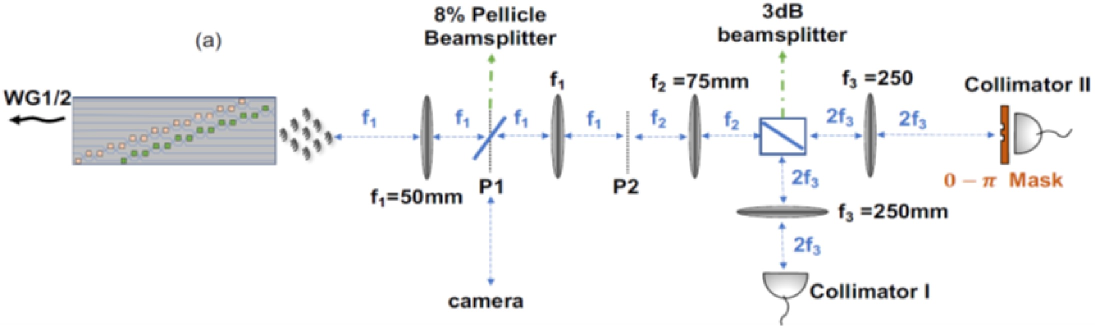
Separating free-space modes

- 9x2 diagonal line mesh
  - separates two orthogonal free-space input modes
  - automatically by self-configuration

M. Milanizadeh, S. SeyedinNavadeh, G. Benci, C. Klitis, M. Sorel, F. Zanetto, G. Ferrari, D. A. B. Miller, A. Melloni, and F. Morichetti, "Multimode free space optical link enabled by SiP integrated meshes," ECOC 21, 13-16 September, 2021, Bordeaux, France, Paper Tu2G.1

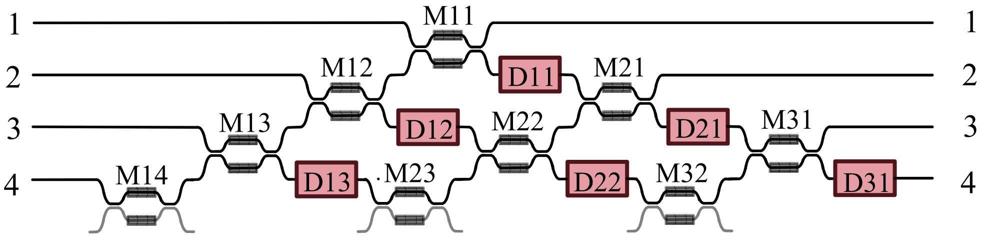
S. SeyedinNavadeh, M. Milanizadeh, G. Benci, C. De Vita, C. Klitis, M. Sorel, F. Zanetto, G. Ferrari, D. A. B. Miller, A. Melloni, and F. Morichetti, "Self-Configuring Silicon-Photonic Receiver for Multimode Free Space Channels," IEEE GFP 2021, 7-10 Dec. 2021, Paper TuE2





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

Note: it is possible to set this up with only detectors at the outputs

though then we may need to "tear down" the network to reconfigure it

Separating multiple orthogonal beams

Input beam(s)
(sampled into
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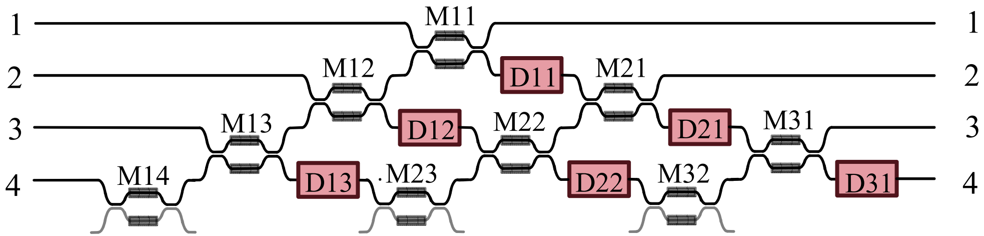


Output
beams

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

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

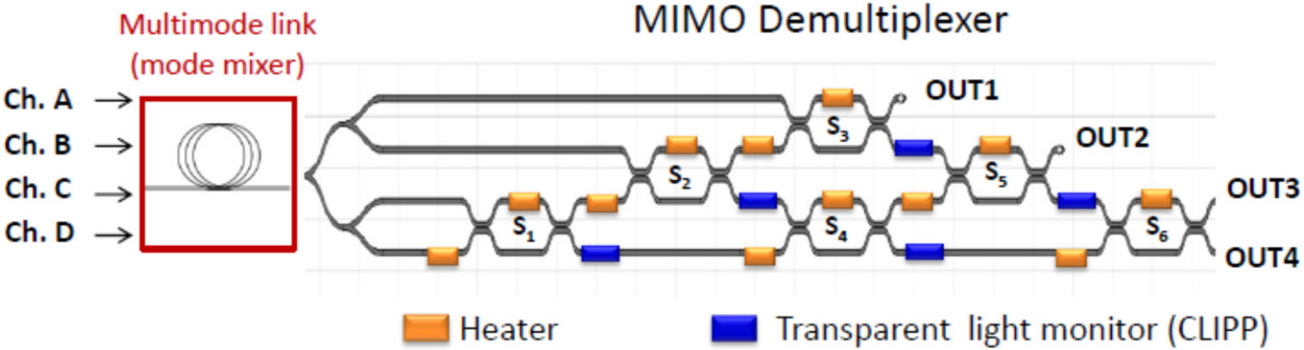
and have the corresponding diagonal row of detectors look for that tone

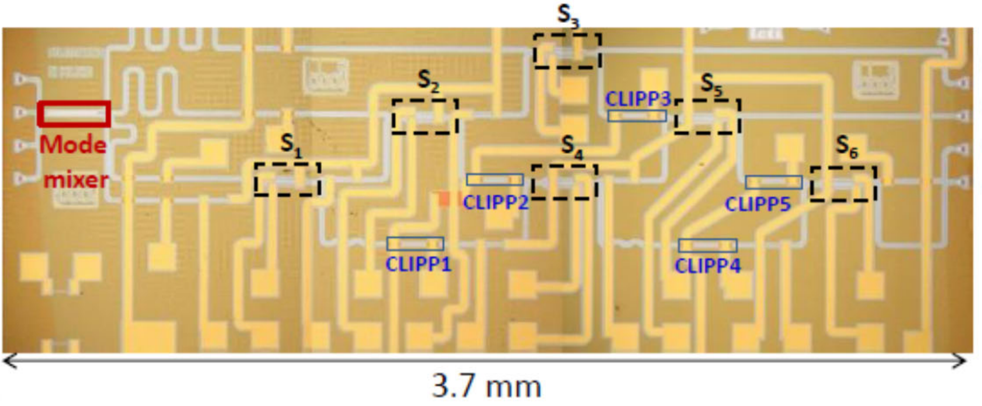
then the mesh can continually adapt to the orthogonal inputs

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

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

based only on maximizing or minimizing power in detectors

to set both beamsplitters to 50:50 after initial fabrication

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

Perfect optics from imperfect components

Importantly

- this does not require any calibrated components
- or balanced detectors to equalize powers

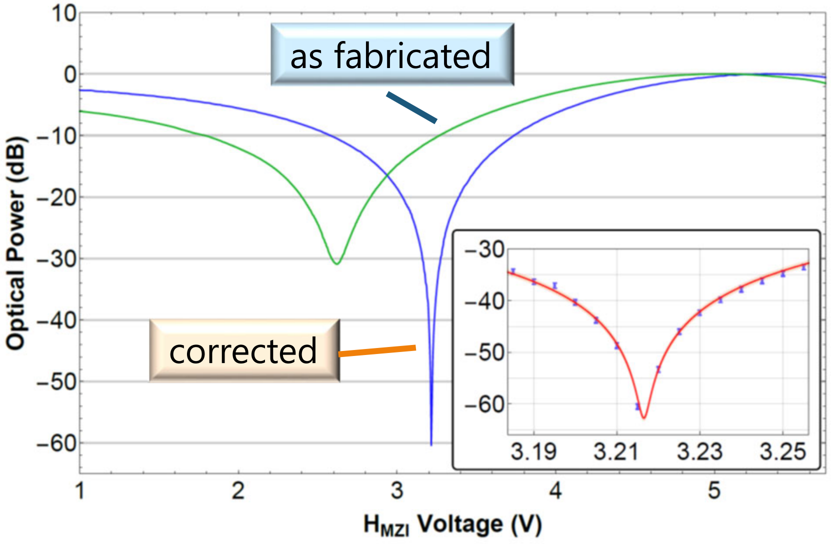
If we use MZIs themselves as effective variable beamsplitters

- the fixed, fabricated split ratios can be as bad as 85:15

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

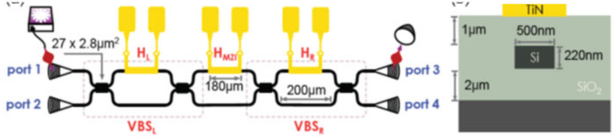
Self-correcting Mach-Zehnder

- 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



as fabricated

corrected



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

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)

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?

Analyzing multimode fields

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 multimode fields

Here we show how do this

- without a coherent reference beam
  - We repurpose our self-aligning beam coupler
    - which can perform all the relevant interferences
      - between all the parts of the beam

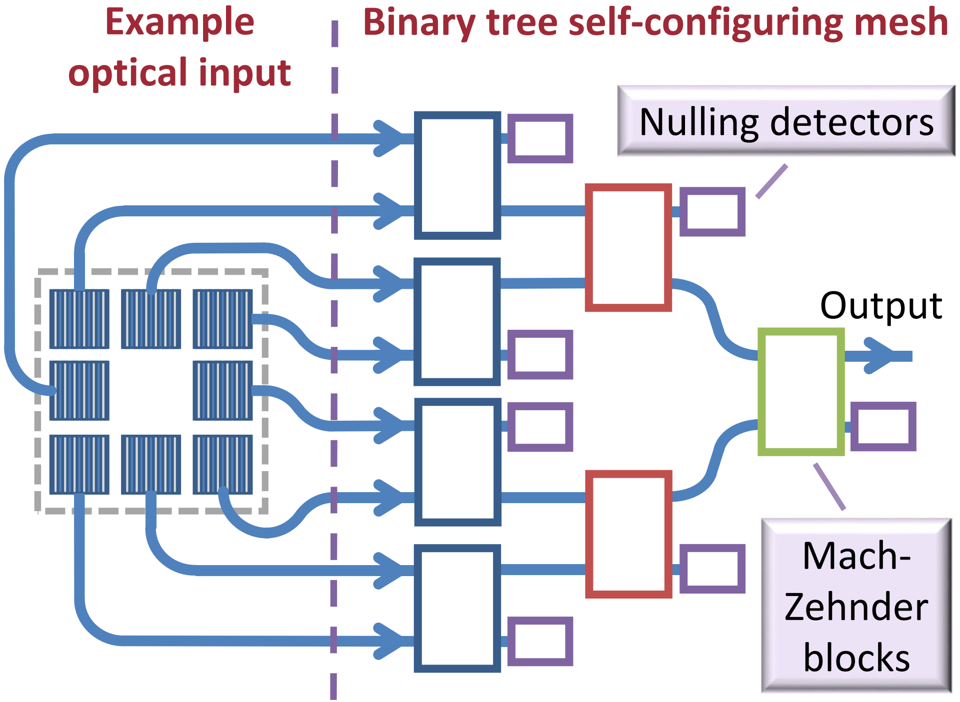
Analyzing a multimode field automatically

If we shine in the beam

and have this mesh network self-align

then from the settings of the phase shifters in the mesh

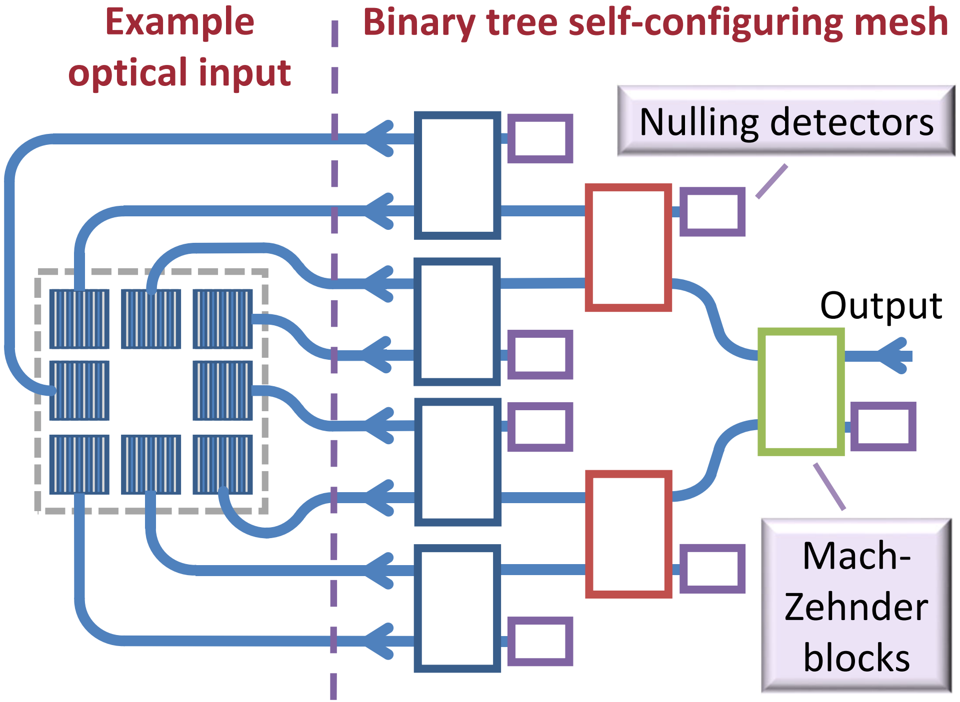
we can simply deduce all the relative amplitudes and phases of the inputs



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

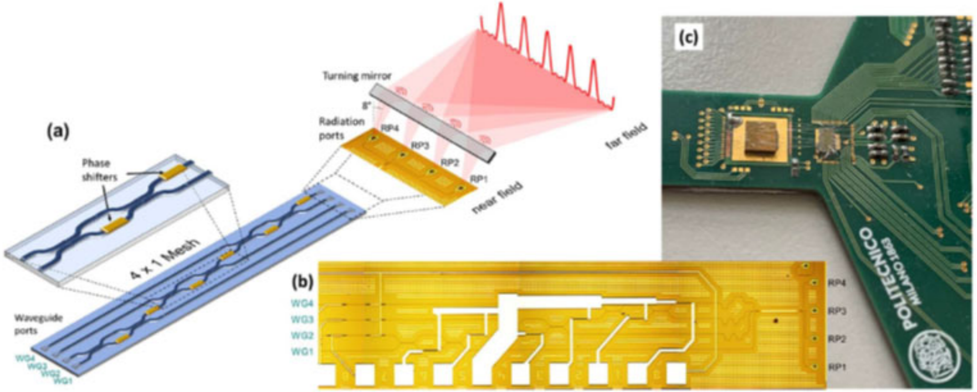


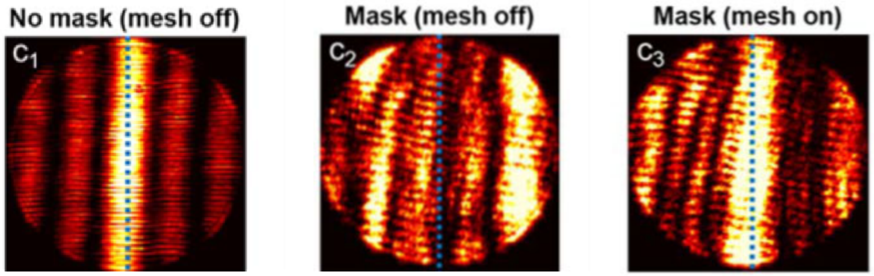
Optica **7**, 794 (2020)

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)

Mask (mesh off)

Mask (mesh on)

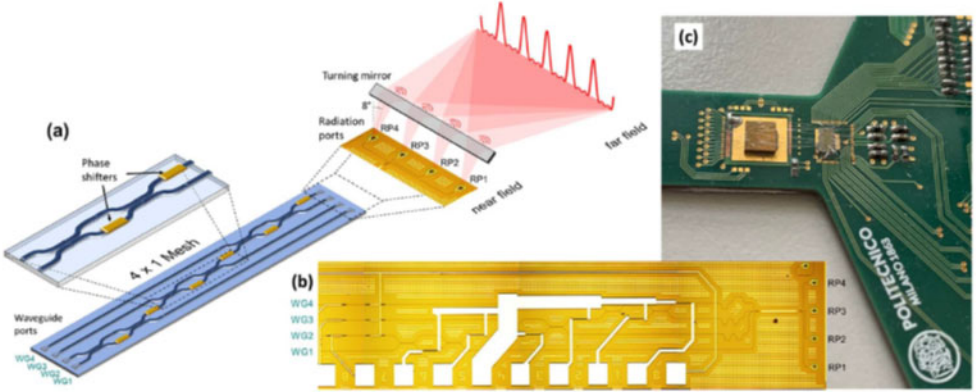
M. Milanizadeh, F. Toso, G. Ferrari, T. Jonuzi, D. A. B. Miller, A. Melloni, and F. Morichetti, "Coherent self-control of free-space optical beams with integrated silicon photonic meshes,". Photonics Research 9, 2196-2204 (2021)

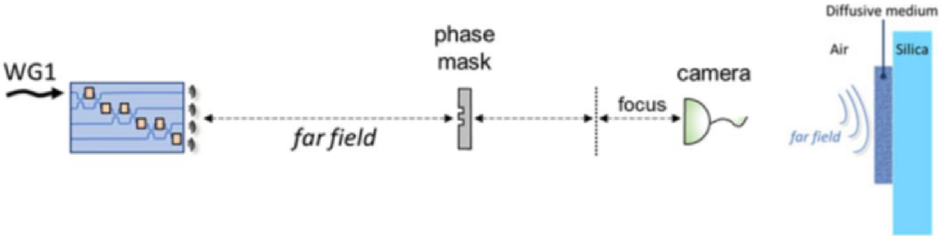
Pre-compensating a beam

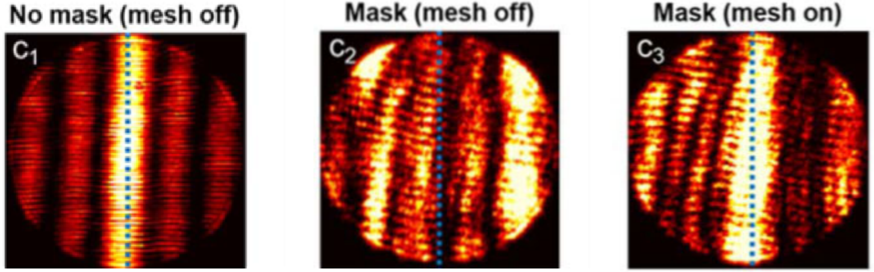
Removing the effects of a diffusing mask with a mesh

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)







Optical setup machines

Quite generally

- we can use a self-aligning beam coupler
  - as an "optical setup machine"
    - A system that can essentially calibrate itself
      - and can be used in reverse
        - to controllably generate arbitrary multimode fields

Setting up other forward networks

We can use such an optical setup machine

- to calibrate and set up other, arbitrary “forward” optical mesh circuits
  - including ones that are not self-configuring, e.g.,
    - lattice filters
    - rectangular or hexagonal meshes

Setting up other forward networks

The key trick is to

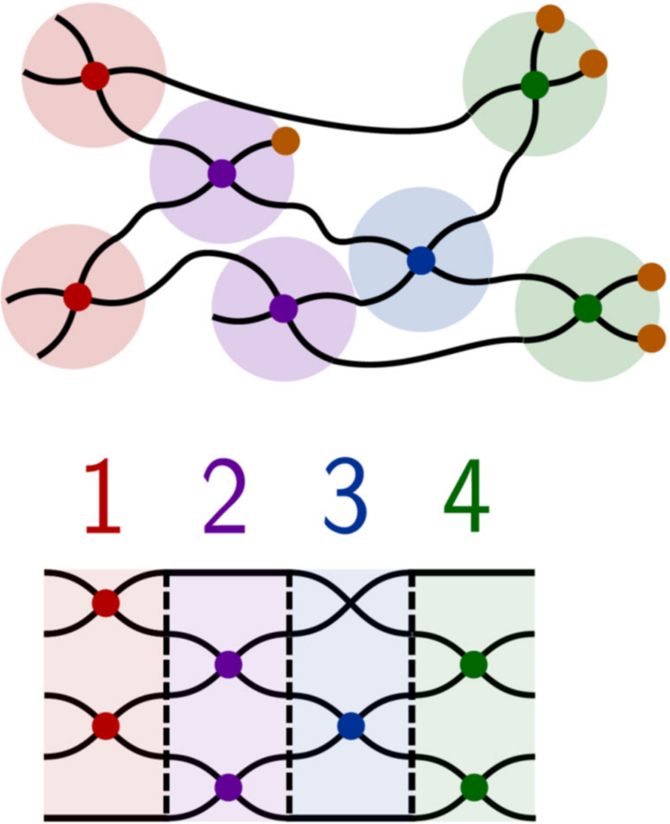
- imagine running the desired network backwards
  - with imaginary light shone into just one port of an MZI
    - The "Reversed Local Light Interference Method" (RELLIM)

Opt. Express **25**, 29233 (2017)

Parallel RELLIM (PRELLIM)

- We can also parallelize this
- Generally a forward-only network can be reorganized into columns
  - while retaining the same topology
- All the nodes in a given column
  - can be set in the same time-step in parallel
    - reducing configuration time

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

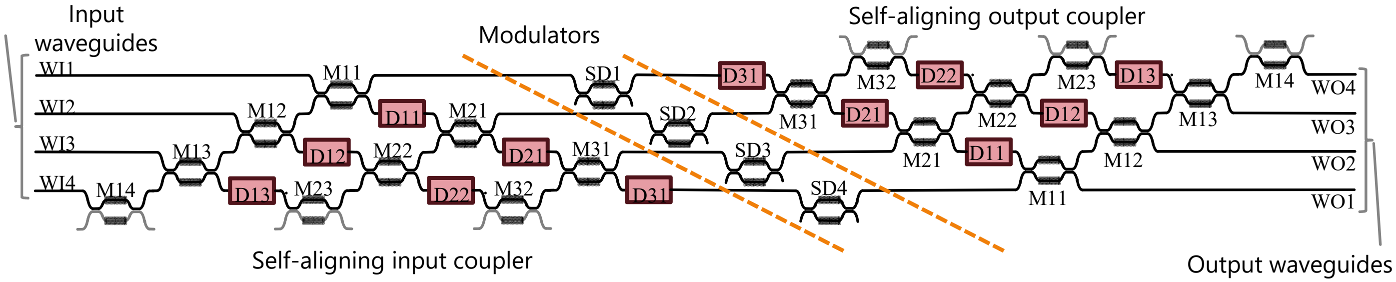


Universal self-configuring photonics

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

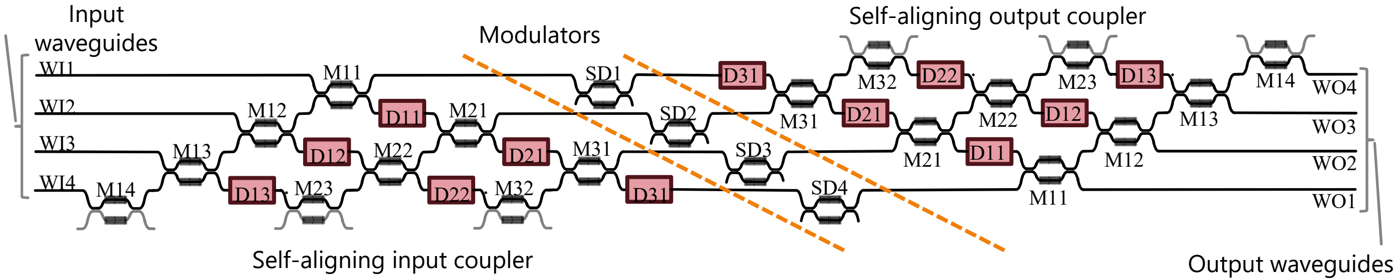
General multiple mode converter



"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)

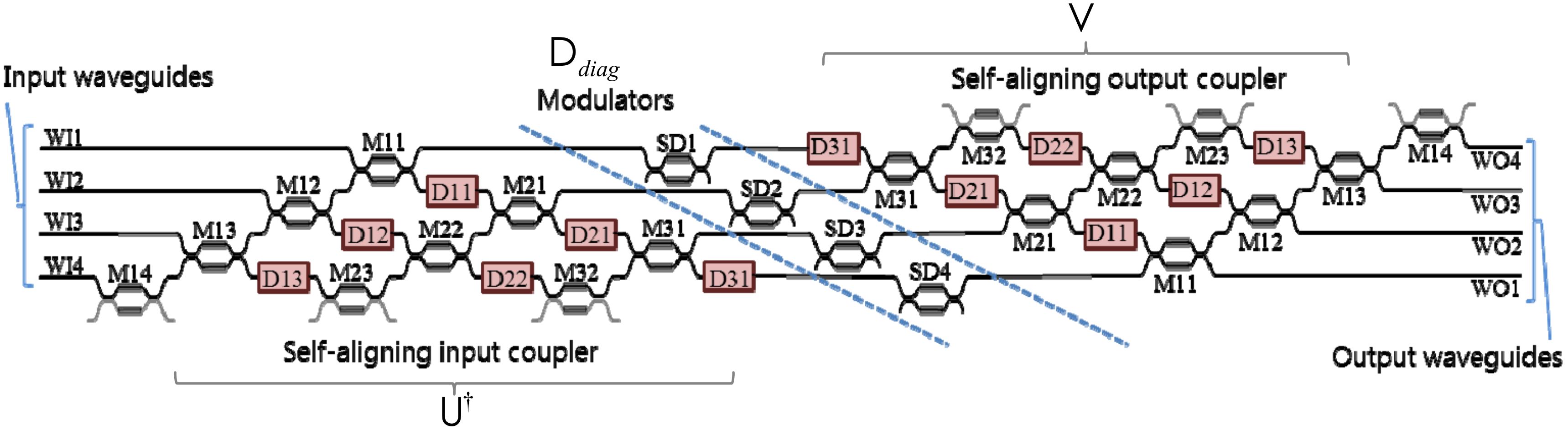
This kind of universal mode conversion, with such modulation

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

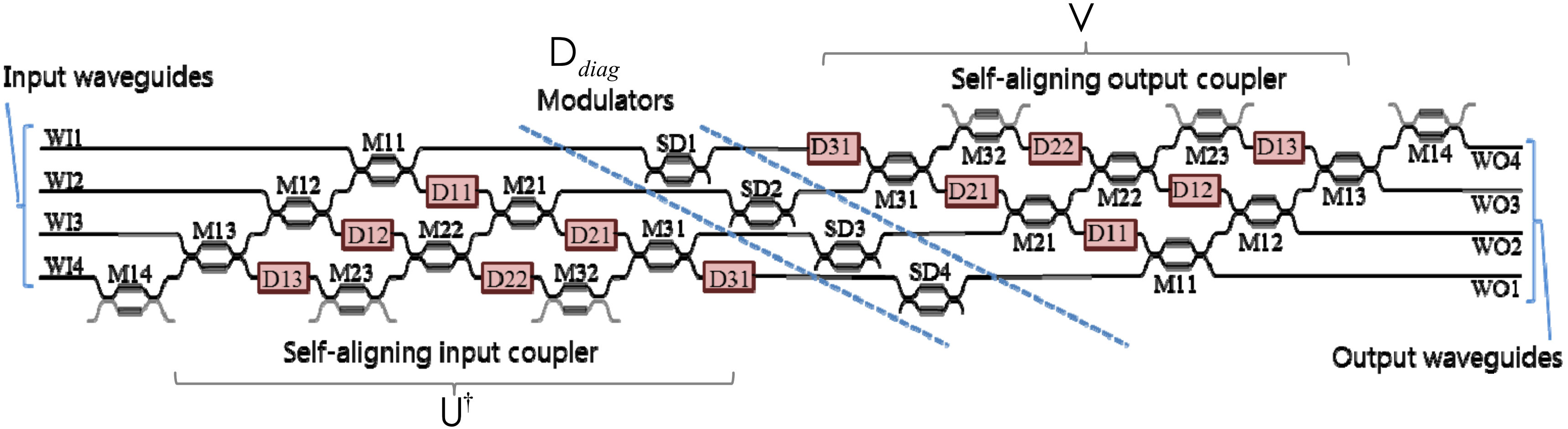
$$D = V D_{diag} U^\dagger$$

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)

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

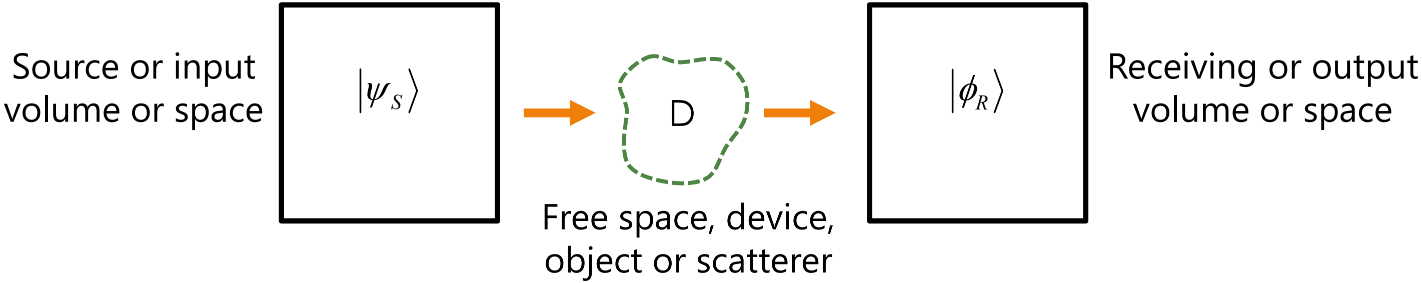
Opt. Express **20**, 23985 (2012)

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)



Source or input volume or space

$|\psi_S\rangle$

D

Free space, device, object or scatterer

$|\phi_R\rangle$

Receiving or output volume or space

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

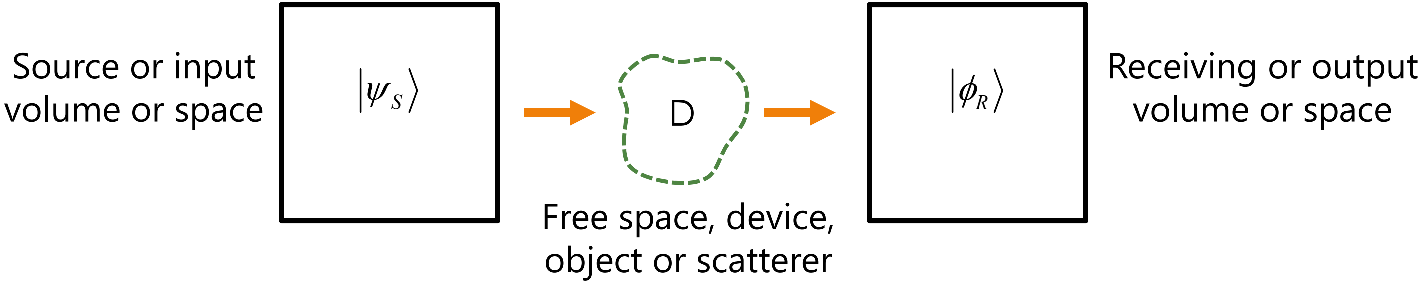
for free-space communications, or for any scatterer, optical device, or object between the spaces

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)



Source or input volume or space

$\left|\psi_S\right\rangle$

D

Free space, device, object or scatterer

$\left|\phi_R\right\rangle$

Receiving or output volume or space

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

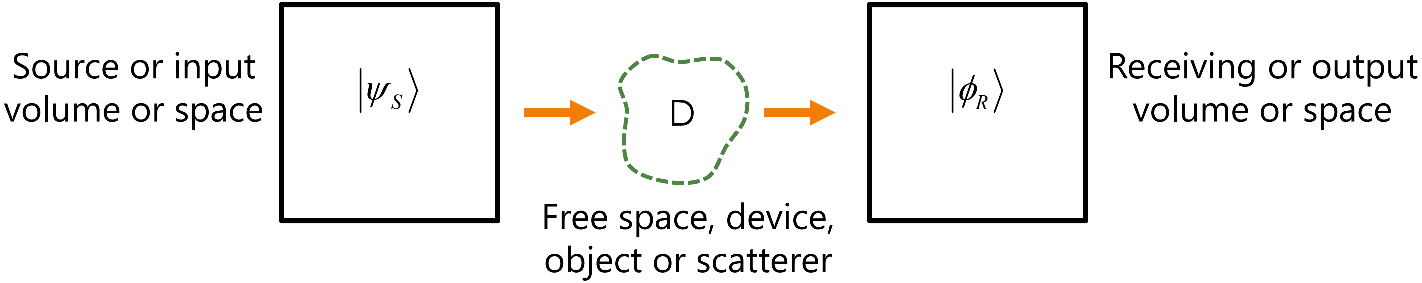
a set of orthogonal source functions $\left|\psi_{Sj}\right\rangle$

that lead, one by one

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

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

Mode-converter basis sets



Source or input volume or space

$|\psi_S\rangle$

D

Free space, device, object or scatterer

$|\phi_R\rangle$

Receiving or output volume or space

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

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

Self-configuring photonics enables complex circuits for new optics

The algorithms to calibrate and use these circuits are

simple and fast

We are just beginning to understand the many uses of these ideas

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

Self-configuring optics references for this talk

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See also “Waves, modes, communications and optics” Adv. Opt. Photon. 11, 679-825 (2019)

For an overview, including all these links, see https://www-miller.stanford.edu/self-configure

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