Reducing energy and increasing capacity – new directions for integrated optics in handling information

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See also D. A. B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications: a Tutorial Review," IEEE/OSA J. Lightwave Technology 35 (3), 343-393 (2017) DOI: 10.1109/JLT.2017.2647779

Two new reasons for complex silicon photonics

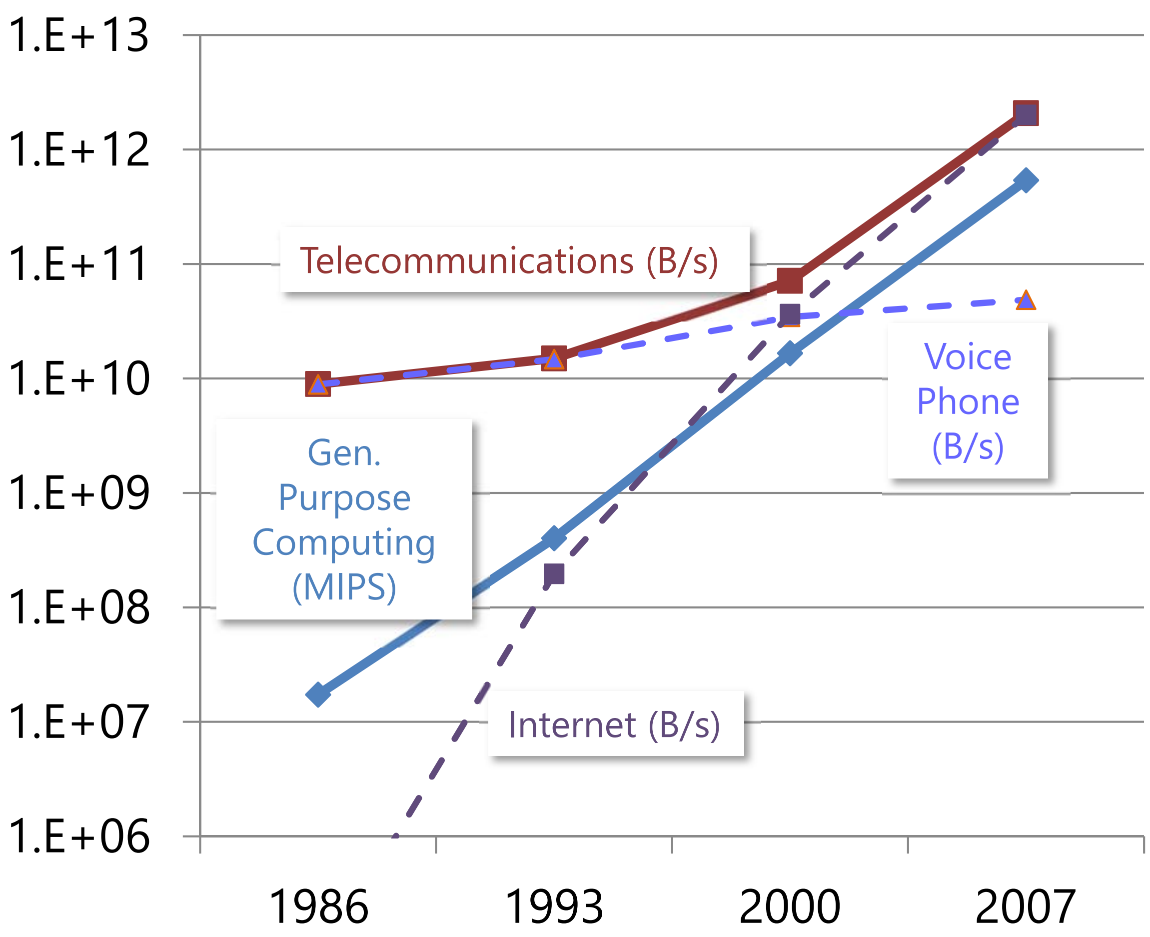
- Saving energy by eliminating the circuits in interconnect links
  - quantum impedance conversion
  - avoiding time-multiplexing in short links

    10–100 fJ/bit total energy instead of 1–10 pJ/bit
- New architectures and algorithms, allow
  - complex circuits to be set up and stabilized
  - self-correcting circuits
  - self-designing circuits

Potential applications in

optical communications sensor preprocessing, arbitrary linear transforms, neural networks, linear optical quantum circuits, …

Growth in information communication and processing



M. Hilbert and P. Lopez, "The World's Technological Capacity to Store, Communicate, and Compute Information," Science 332, 60 (2011)

MIPS – million instructions per second
~ 3 - 6 instructions = 1 floating point operation (FLOP)

- Both
  - Internet traffic
  - General purpose computing hardware
- have grown ~ 60 % per year
  - ~ X 100 in 10 years
- Massive challenge for hardware scaling of
  - Energy
    - Energy per bit has to reduce
      - Energy scaling not environmentally sustainable
        - ~ 4.6 – 9% of electricity in 2012 (Van Heddeghem et al., Computer Comm. **50** 64–76 (2014))
  - Communication density inside systems
    - already at limits for electrical approaches

Energies for communications and computations

Operation	Energy per bit
Wireless data	10 – 30μJ
Internet: access	40 – 80nJ
Internet: routing	20nJ
Internet: optical WDM links	3nJ
Reading DRAM	5pJ
Communicating off chip	1 – 20 pJ
Data link multiplexing and timing circuits	~ 2 pJ
Communicating across chip	600 fJ
Floating point operation	100fJ
Energy in DRAM cell	10fJ
Switching CMOS gate	~50aJ – 3fJ
1 electron at 1V, or **1 photon @1eV**	0.16aJ (160zJ)

most energy is used for communications, not logic

Data rates at different length scales

Total long distance internet traffic ~ 280 Tb/s (Cisco)

- Equivalent to everyone talking on the phone at once all the time

Traffic on "rack to rack" network inside one large data center

- ~ 1 Pb/s (Google)

Graphics processor and server chips peak bandwidth on and off chip

- ~ 1.4 Tb/s – 2 Tb/s

Server processor chip on-chip bandwidths

- on-chip network bandwidth ~ 4 Tb/s
- bandwidth in and out of L3 cache ~ 12.8 Tb/s

DM, JLT **35**, 343 (2017)

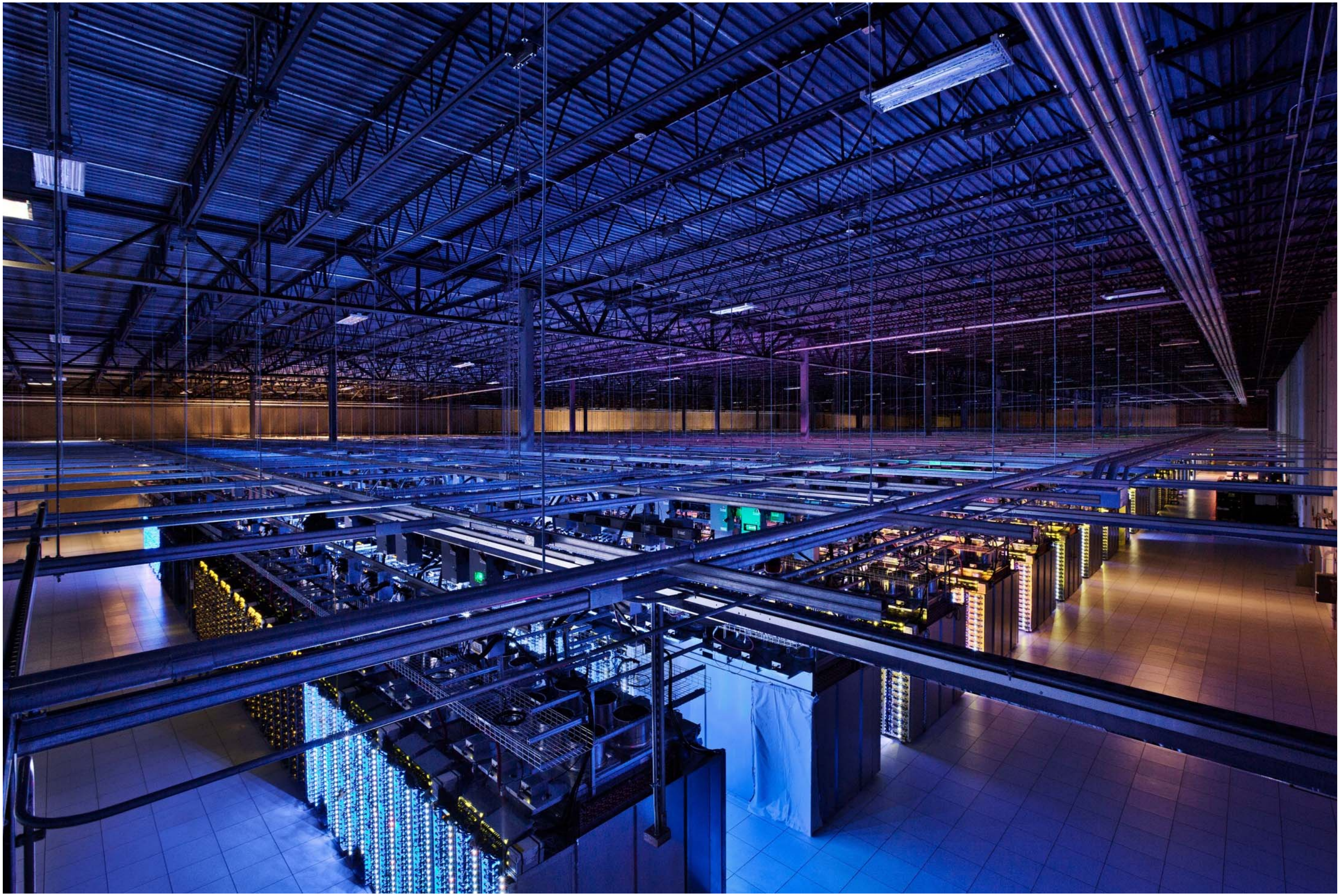
Energy and information

Though it does take more energy to send a bit over longer distances

there is massively more information sent at shorter distances

so much so that

most energy dissipation is in shorter links and in interconnects inside machines



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Capacitance of small structures for fJ operation

Structure	Capacitance
100×100μm square conventional photodetector	~1pF
5×5μm CMOS photodetector	4fF
Wire capacitance, per μm	~200aF
FinFET input capacitance	~ 20 – 200 aF
1 micron cube of semiconductor	~100aF
100 nm cube of semiconductor	~10aF
10 nm cube of semiconductor	~1aF

So that capacitive charging energies do not dominate, we need

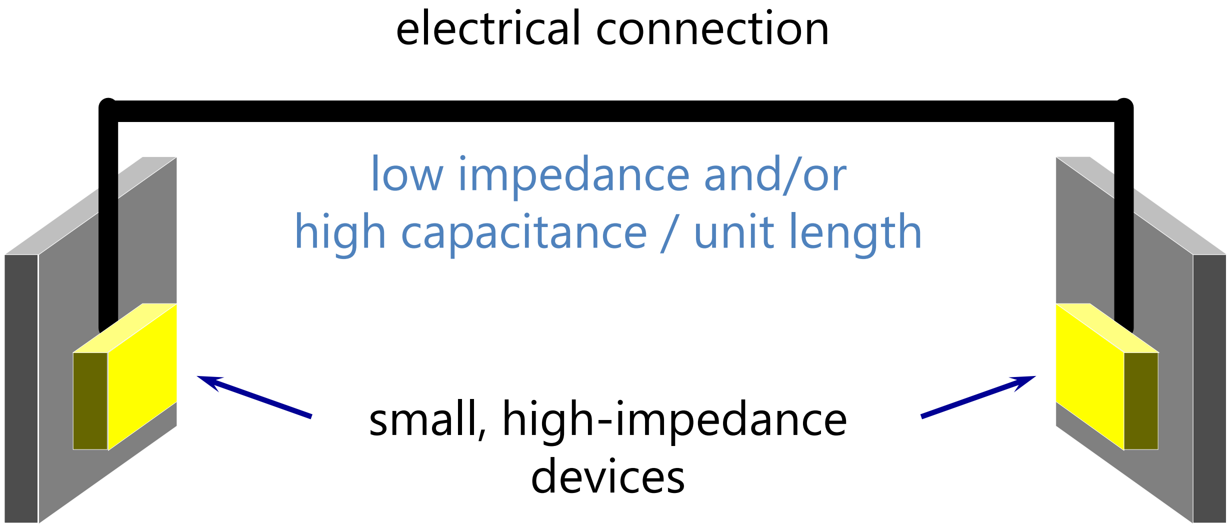
small devices for low device capacitance

very close integration to limit wiring capacitance

DOI: 10.1109/JLT.2017.2647779

Power dissipation in electrical wires

- Wires always have large capacitance per unit length
  - ~ 2 pF/cm, 200 aF/micron
- Simple logic-level signaling results in large dissipation
  - Dissipate at least $\sim \frac{1}{4}CV^2$ per bit in on-off signaling
  - E.g., at 2pF/cm and a 2 cm chip, at 1 V on-off signaling
    - energy per bit communicated at least ~ 1pJ



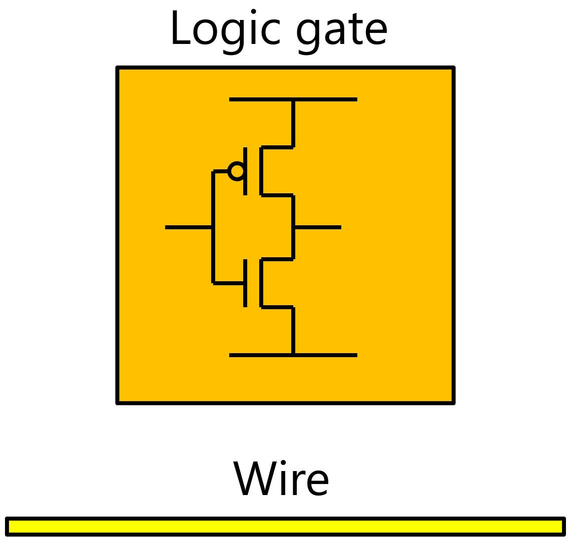
electrical connection

low impedance and/or
high capacitance / unit length

small, high-impedance
devices

Logic and wiring capacitance

- Wiring capacitance even to neighboring gates is
  - comparable to or greater than the transistor capacitance
- Most energy in information processing is in communications
  - not in logic
    - even at the gate level
- Most energy dissipation in information processing is in
  - charging and discharging wire capacitance
    - which is ~ 200 aF/micron
- Just “touching” a bit typically costs many fJ in CMOS



Energy and information

The dominant energy dissipation at short distances inside machines

is charging and discharging wire capacitance

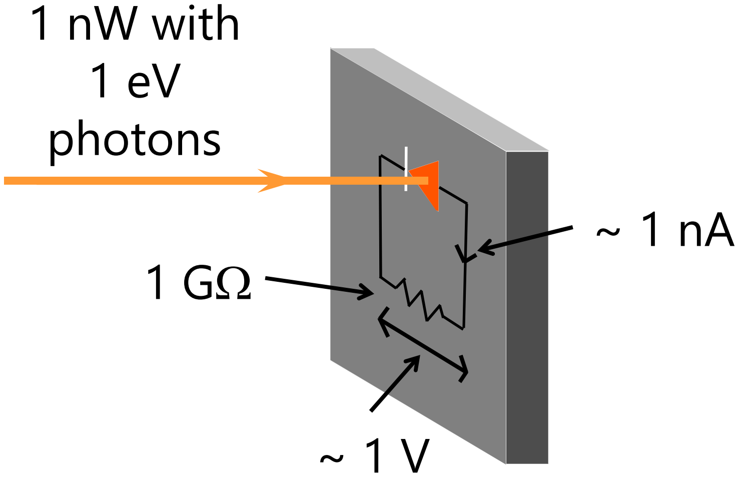
Quantum impedance conversion

The photoelectric effect

- means it is possible to generate a "large" voltage in a detector (e.g., a fraction of a volt), with
  - very little signal power or energy
  - and very little classical voltage in the light beam (< 1mV for 1nW)
- "quantum impedance conversion"

Optics only has to charge the photodetector and transistor to the logic voltage

- not the interconnect line



DM, Optics Letters, **14**, 146 (1989)

How use optics to avoid charging wires?

To exploit quantum impedance conversion, need to reduce energy in optoelectronic devices

- so the energy to send information optically becomes
  - less than that of wires
    - even for short distances
      - e.g., centimeters or even shorter
- Low energy optoelectronic devices
  - Pushing operating energies into the sub 10fJ or even attojoule range for output devices
    - Modulators, LEDs, lasers
      - including advanced nanophotonic structures
  - Integrating sub-fF photodetectors right beside transistors

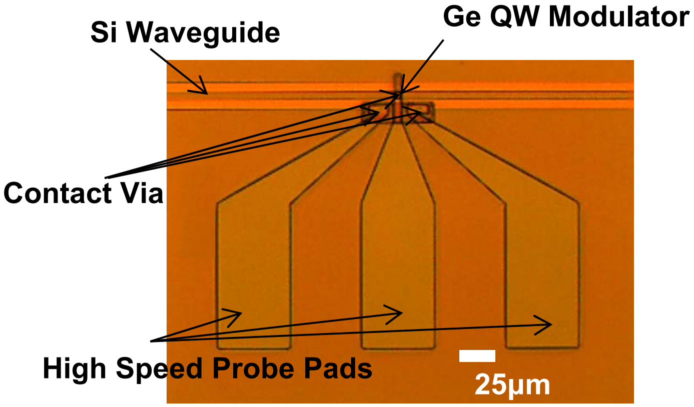
DM, JLT **35**, 343 (2017)

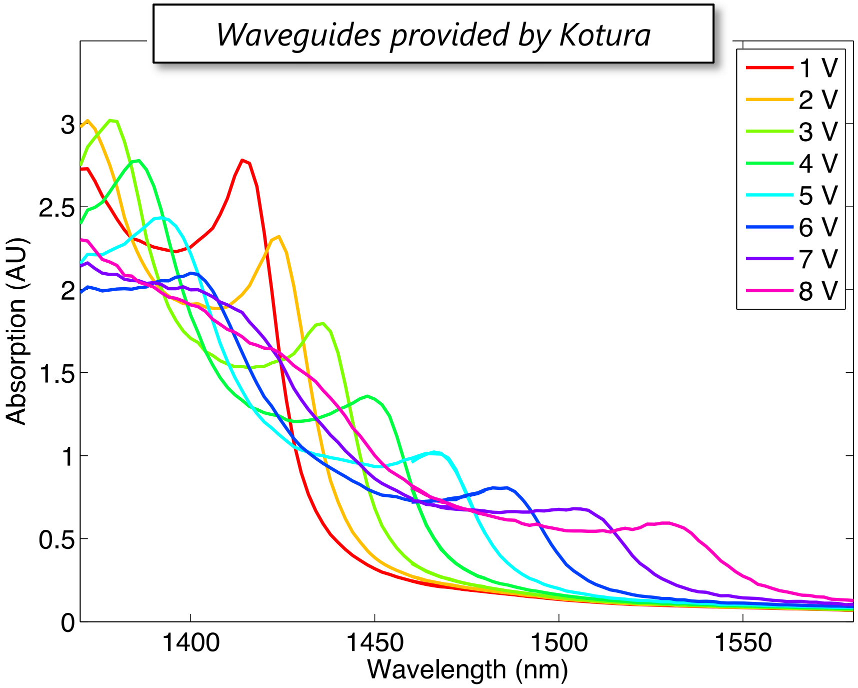
First Ge quantum well waveguide-integrated modulator

- 10 microns long, 0.8 microns wide, 500 nm thick intrinsic region
  - **On silicon**
  - **No resonator**
- Selective area growth of quantum wells in SOI waveguides
  - Capacitance ~ 3 fF
- 3 dB modulation with 4 V bias, 1 V swing, 1460 nm
  - Dynamic energy per bit ~ ***0.75 fJ***
- Tested to 7Gb/s (equipment limited)

S. Ren et al., IEEE PTL 24, 461 – 463 (2012)
D. A. B. Miller, Optics Express 20, A293-A308 (2012)

Harris and Miller groups, Stanford




Waveguides provided by Kotura

Need to move to optics to save energy

- **New additional conclusion** - Avoid wasting energy in the electrical circuits used to run interconnects
  - low energies in optoelectronic devices themselves cannot be exploited effectively if the dissipation in the associated circuits is large
    - e.g., receiver amplifier circuits dissipating 100’s fJ/bit to pJ’s/bit
    - e.g., time-multiplexing circuitry dissipating pJ’s/bit
      - clock and data recovery (CDR)
      - serialization/deserialization (SERDES)
      - clock distribution

DM, JLT **35**, 343 (2017)

Eliminating receiver energy

Integrate low capacitance photodetectors beside transistor input

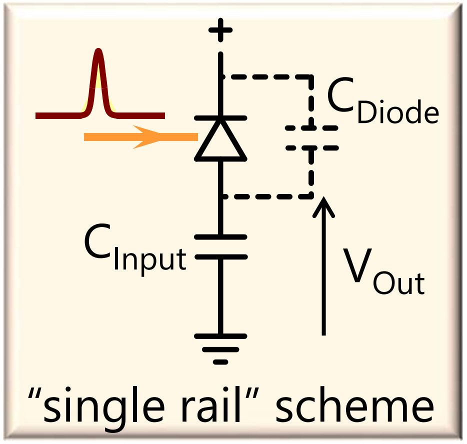
- may eliminate need for voltage amplification altogether
  - **receiverless** operation
- or limit it to ~ one simple low energy gain stage
  - **“near-receiverless”** operation

DM, JLT **35**, 343 (2017)

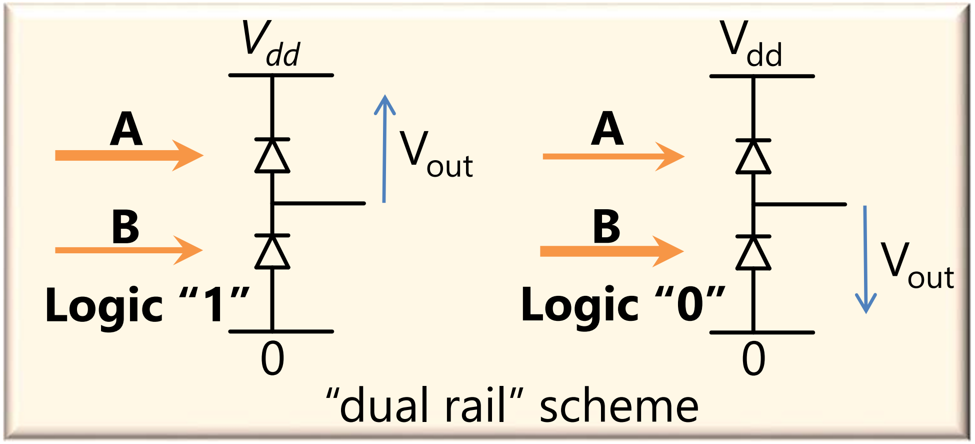
E.g., with 1 fJ received optical energy

- in 1 pF, generates ~1 mV
- in 30 fF (solder-bumped photodetector), generates ~33 mV
- in 1 fF, generates ~1 V

“Dual rail” schemes also eliminate need for AC coupling and line coding



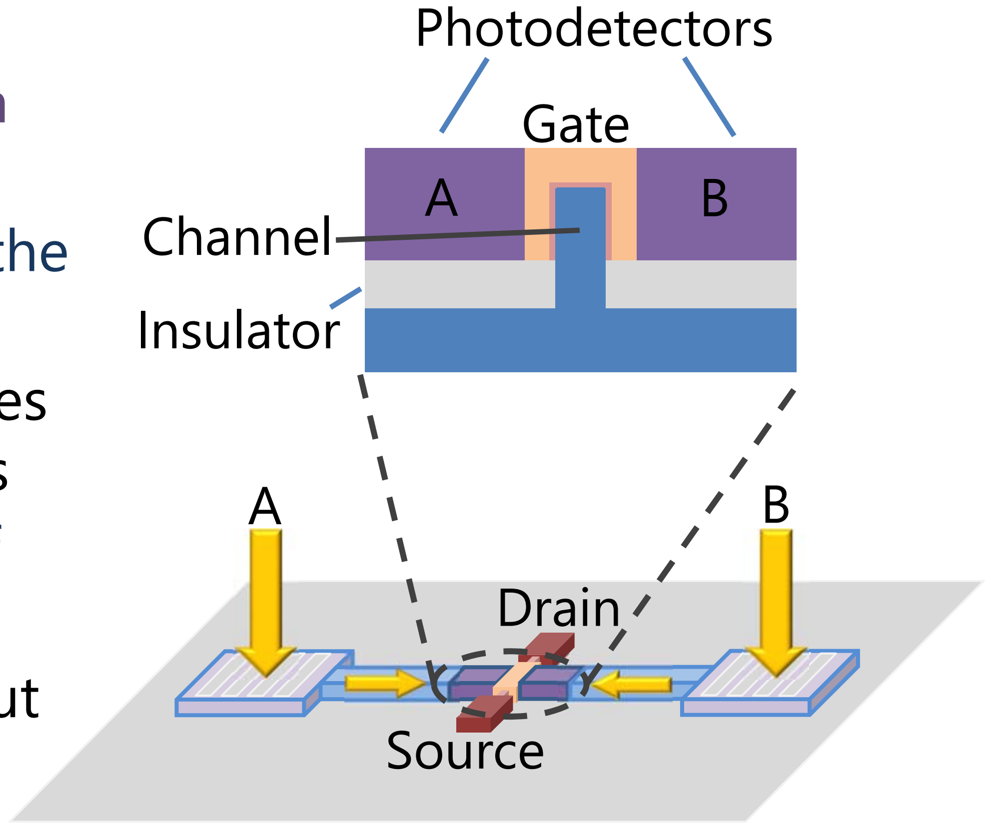
“single rail” scheme



“dual rail” scheme

Eliminating receiver energy

- Integration of optoelectronics right beside transistors
    - e.g., within < a micron or a few microns at most
  - allows excess capacitance in the scale of only 100’s of aF
- Photodetector elements on scales of 1 micron or less dimensions
  - allow detector capacitance of ~100 aF
- Transistors themselves have input capacitances
  - ~ 10’s to 100’s of aF
- Hence <1fF total capacitance
  - possible with integration



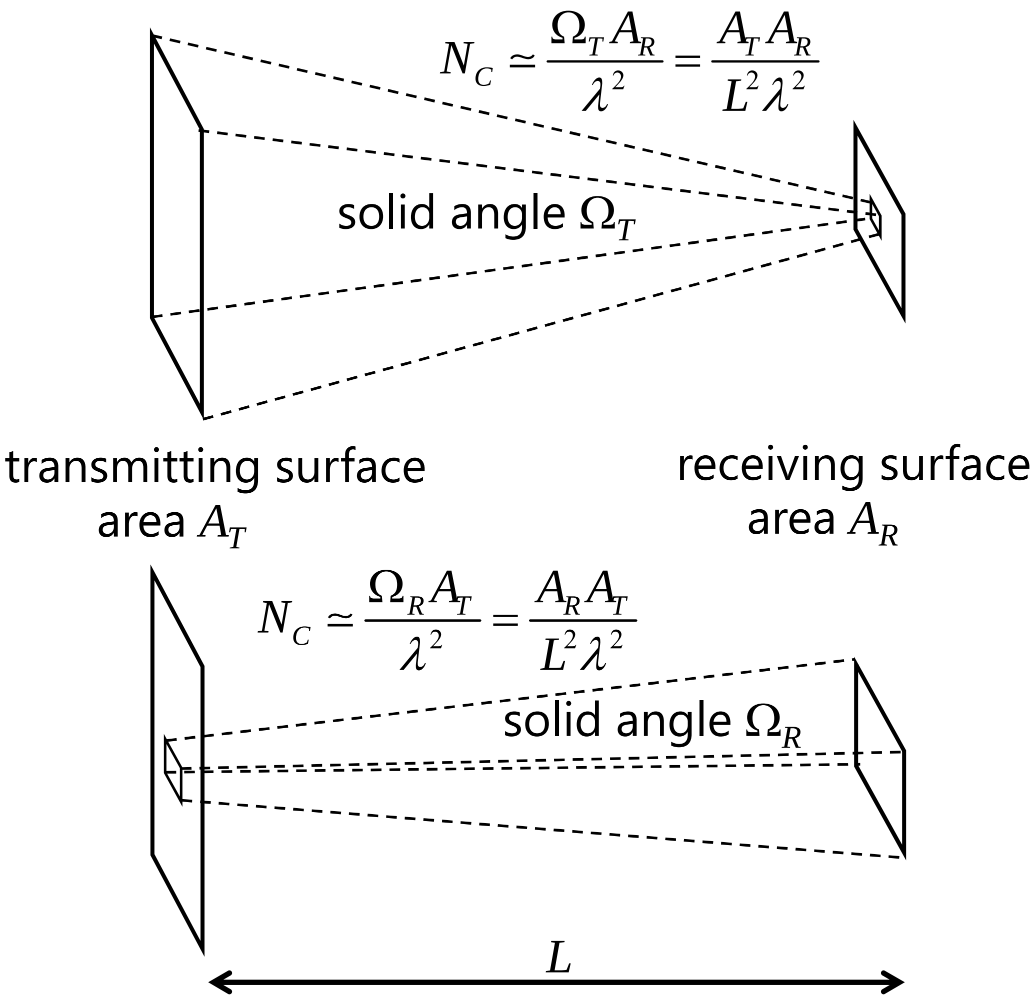
DM, JLT **35**, 343 (2017)

Eliminating multiplexing and timing energies

- Avoid time multiplexing
  - run interconnects at the logic IC clock rates (e.g., 1 – 2 GHz)
    - by using massive numbers of optical channels
      - **eliminates the serialization/deserialization (SERDES) circuits**
- Avoid need for data timing realignment
  - Optics has well-defined propagation time, so we
    - can run optical links with deterministic "integer" lengths
      - i.e., integer numbers of clock cycles
        - viable up to, e.g., 10 m lengths even over 0 – 100 C temperature ranges
      - **eliminates the clock and data recovery (CDR) circuits**

DM, JLT **35**, 343 (2017)

Number of possible free-space channels



$$N_C \simeq \frac{\Omega_T A_R}{\lambda^2} = \frac{A_T A_R}{L^2 \lambda^2}$$

$$N_C \simeq \frac{\Omega_R A_T}{\lambda^2} = \frac{A_R A_T}{L^2 \lambda^2}$$

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The number of possible optical channels (per polarization)
- between two surfaces of areas A_1 and A_2
  - separated by a distance L
    - at a wavelength λ
      - as limited by diffraction, is

$$\boxed{N_C \simeq \frac{A_T A_R}{L^2 \lambda^2}}$$

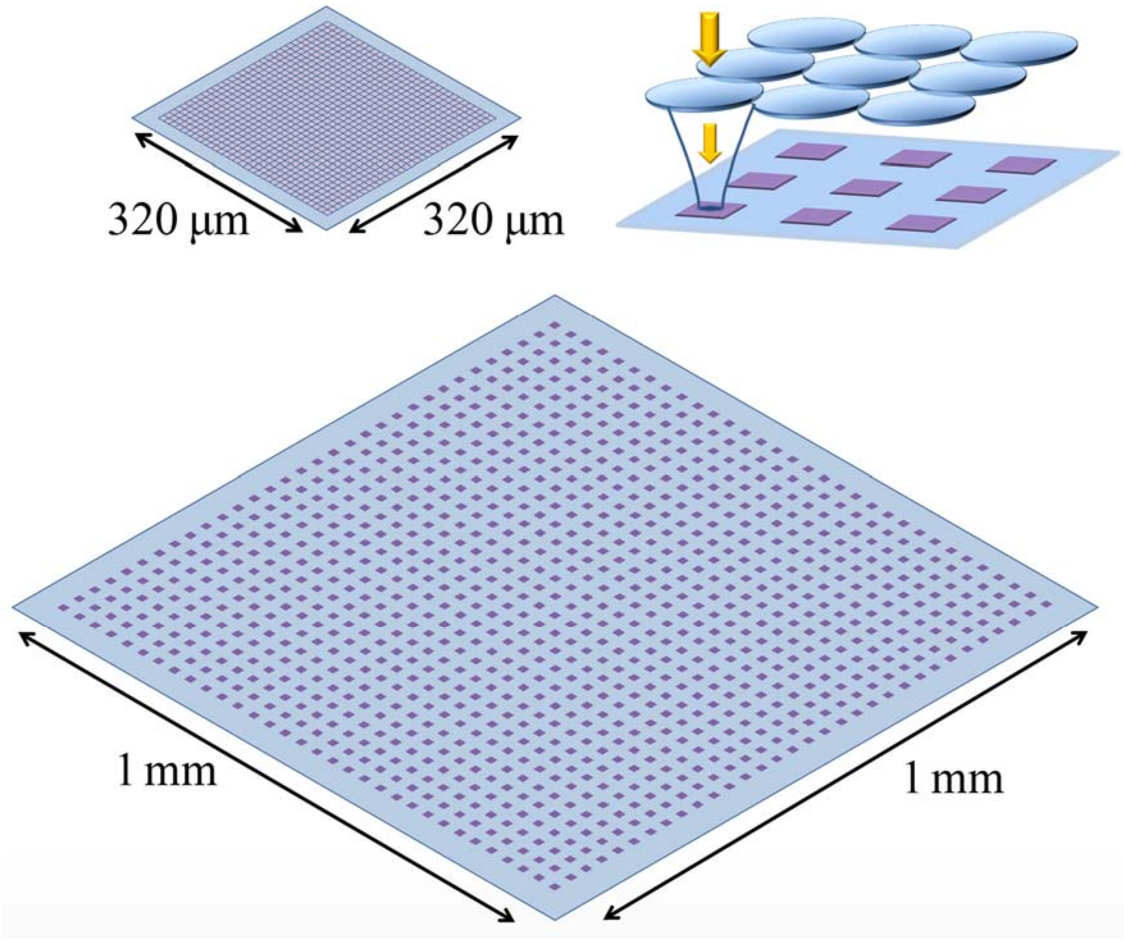
e.g., at 1 μm wavelength
- for 10 cm x 10 cm surfaces separated by 10 m

$$N_C \simeq 10^6$$

- for 2mm x 2mm surfaces separated by 2 cm

$$N_C \simeq 4 \times 10^4$$

2D arrays of 1024 free space channels



E.g., 10 x 10 micron optical "pads"

either packed closely

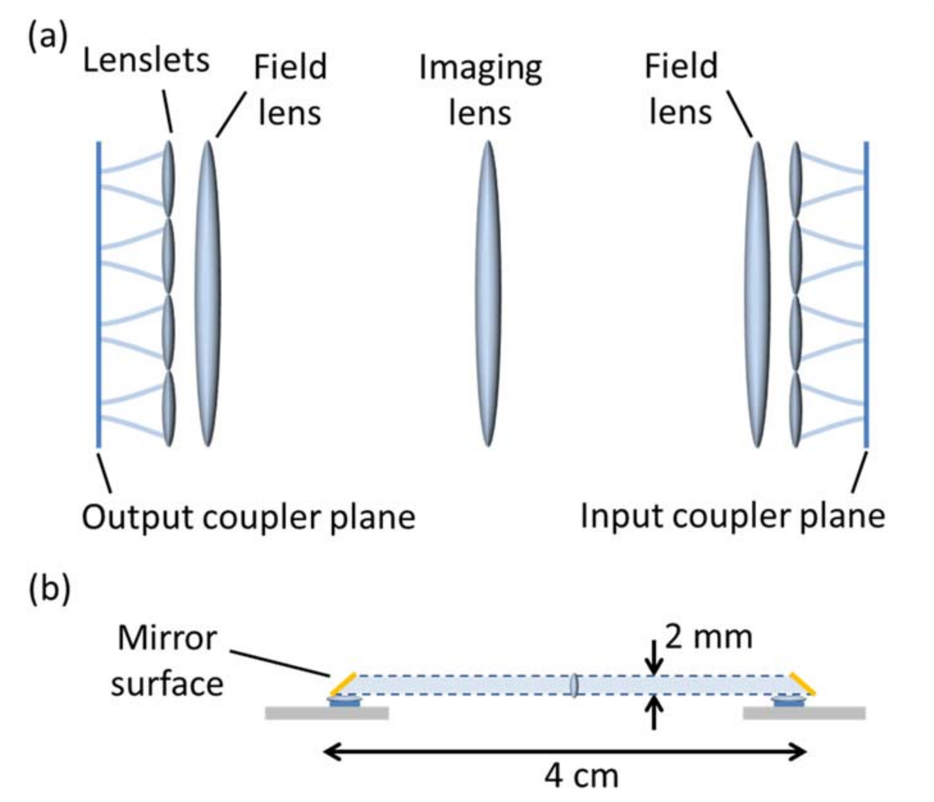
or spaced out, and using lenslet arrays

DM, JLT **35**, 343 (2017)

Free-space optical system approaches

- free-space optics in large arrays
  - 1000’s or 10,000’s or channels
    - even running at energy efficient clock-rates
      - e.g., 2 GHz
    - can allow multiple Tb/s on and off chip
    - even in only square millimeters of chip area
- channels can be to
  - neighboring chips on a board
  - or different boards or racks

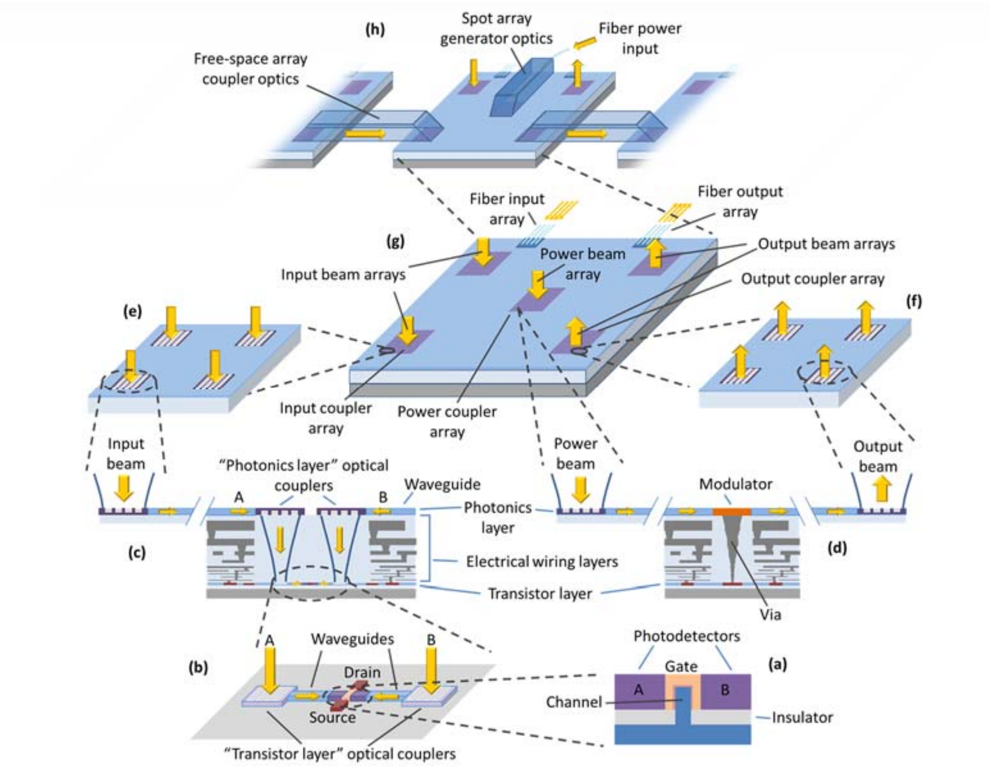
DM, JLT **35**, 343 (2017)



see also J. M. Kahn and D. A. B. Miller, “Communications expands its space,” Nature Photonics 11, 5 – 8 (2017) doi:10.1038/nphoton.2016.256

An example low energy system approach

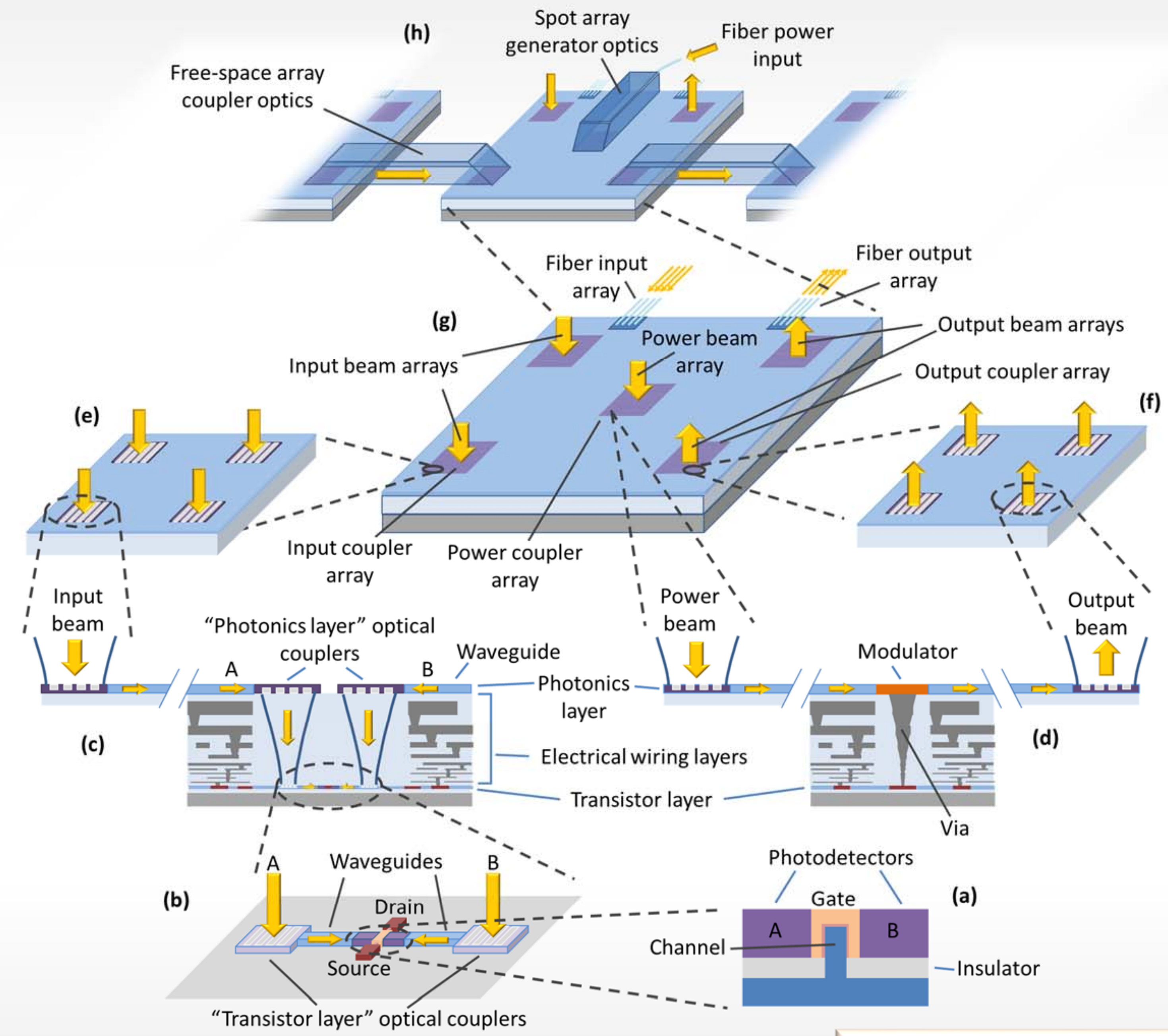
- Key additional technology
  - use a silicon photonics optical “interposer” layer
    - especially with additional materials
      - e.g, III-Vs, germanium
  - optical couplers, including
    - optical vias
    - waveguide arrays
    - free-space couplers
- Key desireable advance
  - beam and mode couplers with
    - %’s of loss, not dB’s of loss
      - major opportunity for nanophotonics
- Goal – 10 fJ/bit up to 10 m distance



“Straw man” system concept exploiting

- tightly integrated optoelectronics
- efficient beam couplers
- free-space communications with 1000’s to 10,000’s of channels

DM, JLT **35**, 343 (2017)



DM, JLT **35**, 343 (2017)

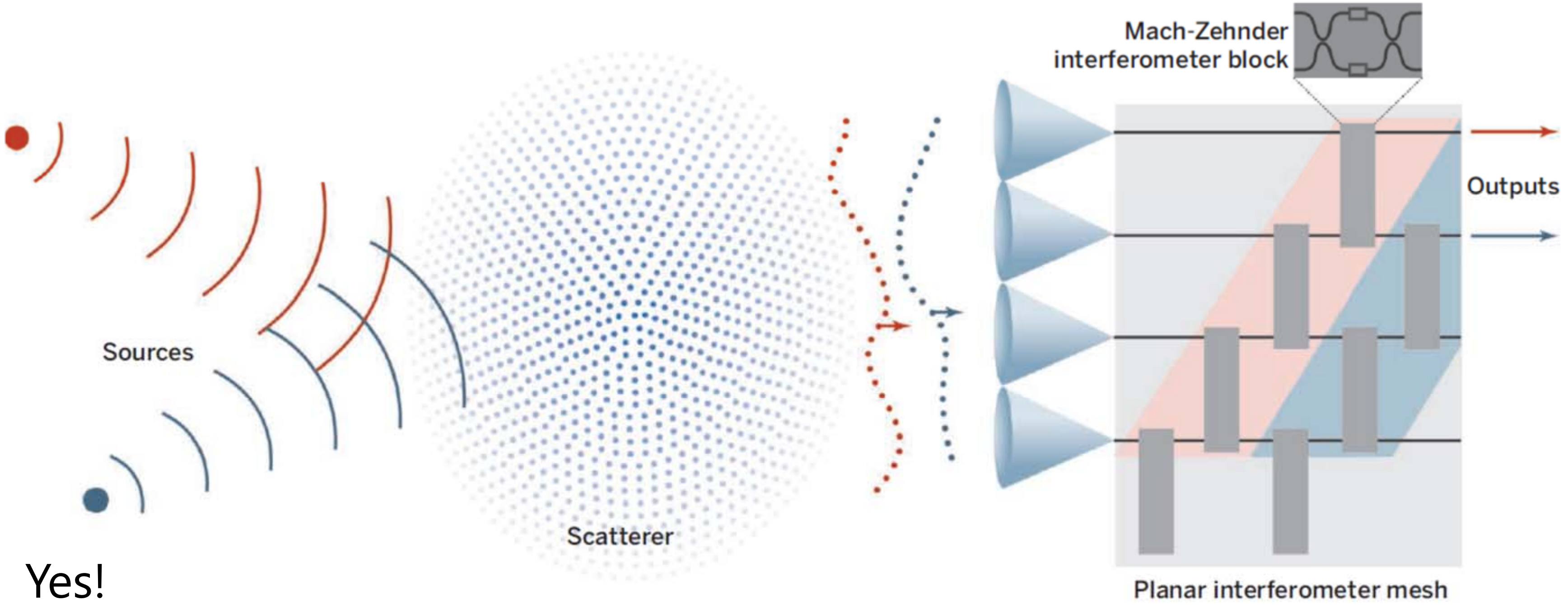
Two new reasons for complex silicon photonics

- Saving energy by eliminating the circuits in interconnect links especially eliminating time-multiplexing in short links
  10–100 fJ/bit total energy instead of 1–10 pJ/bit
- New architectures and algorithms, allow
  - complex circuits to be set up and stabilized
  - self-correcting circuits
  - self-designing circuits

Potential applications in

optical communications, sensor preprocessing, arbitrary linear transforms, neural networks, linear optical quantum circuits, …

Can we disentangle light beams?



Yes!

There is a way of undoing complicated scattering to separate out channels

automatically, without calculations or calibrations

based on self-configuring meshes of interferometers

e.g., in silicon photonics circuits

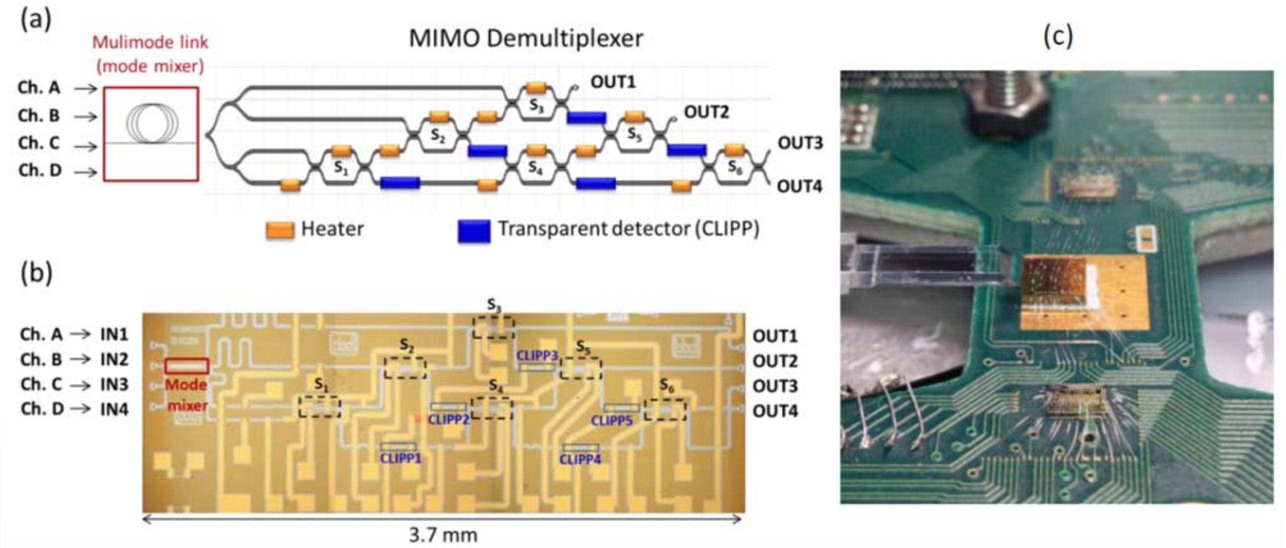
"Sorting out light,"
Science **347**, 1423 (2015)

Applications

- demultiplexing of signals in multimode fibers and waveguides

  losslessly separating overlapping light beams of different shapes
- circuits for coherent communications, tracking polarization
- sensor preprocessing, arbitrary linear transforms, neural networks
- self-aligning beam couplers and beam combiners
- tracking a source in three dimensions, undoing optical scattering
- linear optical quantum circuits, quantum computing gates
- microwave photonics

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)
Politecnico di Milano



Recent work on mesh optics

Self-configuring and self-correcting optics demonstrations

- 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)
- 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)

Other recent mesh demonstrations

- 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)
- D. Pérez, I. Gasulla, J. Capmany, and R. A. Soref, "Reconfigurable lattice mesh designs for programmable photonic processors," Opt. Express 24, 12093-12106 (2016)
- 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) doi: 10.1364/OPTICA.2.000854

Theory of universal and self-configuring/correcting optics

- DM, "Self-configuring universal linear optical component," Photon. Res. 1, 1-15 (2013)
- DM, "Perfect optics with imperfect components," Optica 2, 747-750 (2015)
- DM, "Setting up meshes of interferometers – reversed local light interference method," Opt. Express 25, 29233-29248 (2017)

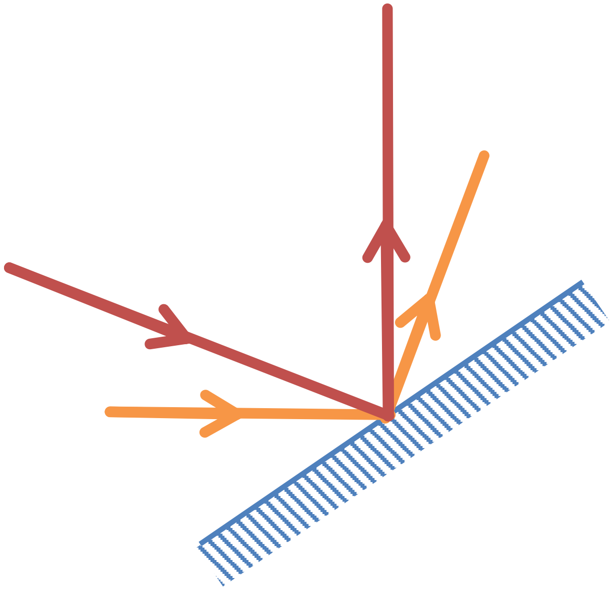
Simple optical components – a mirror

We “design” a plane mirror

- by choosing its angle
  - so it takes a beam of one angle
    - and changes it into a beam of another angle

For another beam at another angle

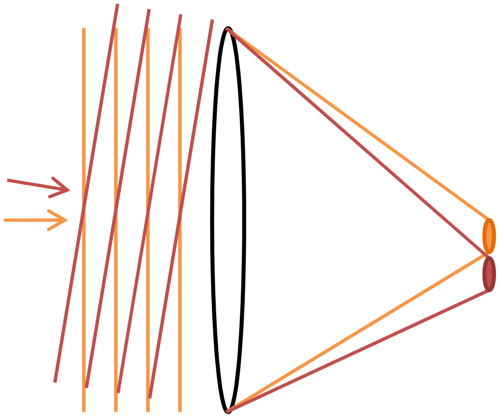
- the mirror changes it to a beam of yet another angle
  - but we have no independent control
    - of what happens for the second beam



Simple optical components – a lens

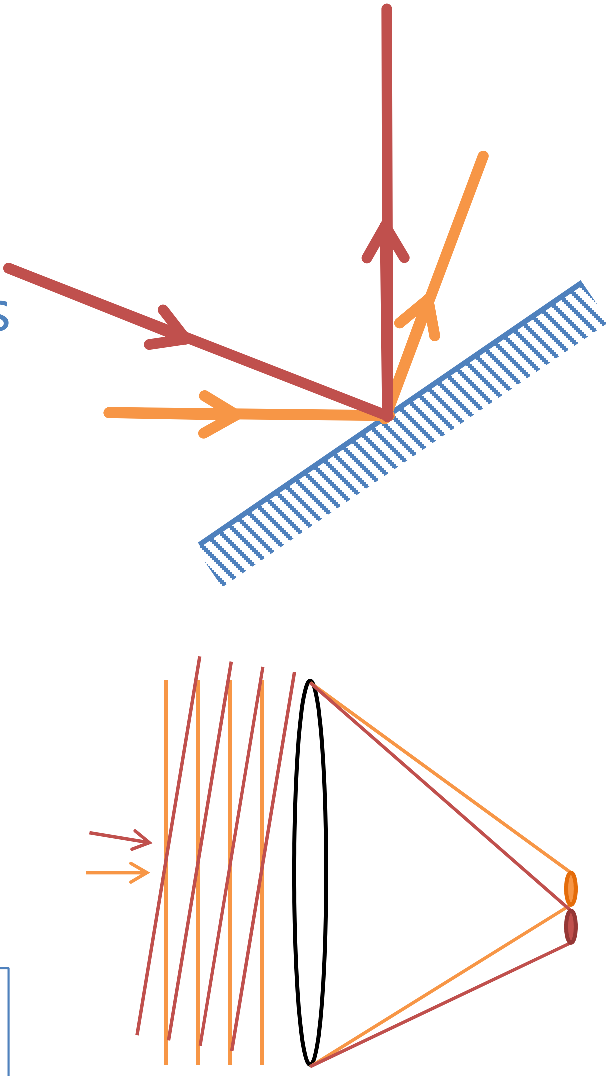
We design a lens
- by choosing its index and curvatures
  - so it takes a plane wave in one direction
    - and focuses it to a spot

For another plane wave in another direction
- the lens focuses it to another spot
  - but we have no independent control
    - of what happens for the second beam

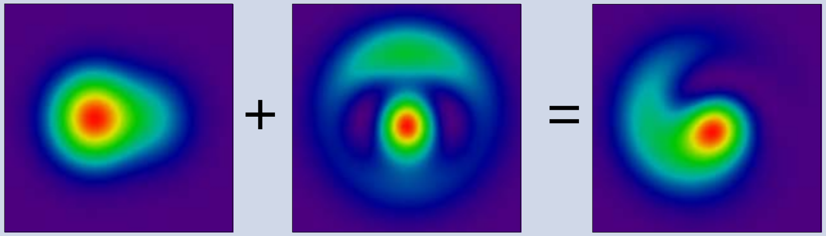


Simple “thin” optical components

- This kind of behavior is general for “thin” optical components
  - e.g., thin holograms, diffractive optical elements
  - spatial light modulators, adaptive optics
  - metasurfaces
- We design them to perform some useful function for one input beam
  - but we have no independent control of what happens
    - for other beams
- So these are not “arbitrary” optical components



"How complicated must an optical component be?"
J. Opt. Soc. Am. A 30, 238-251 (2013)



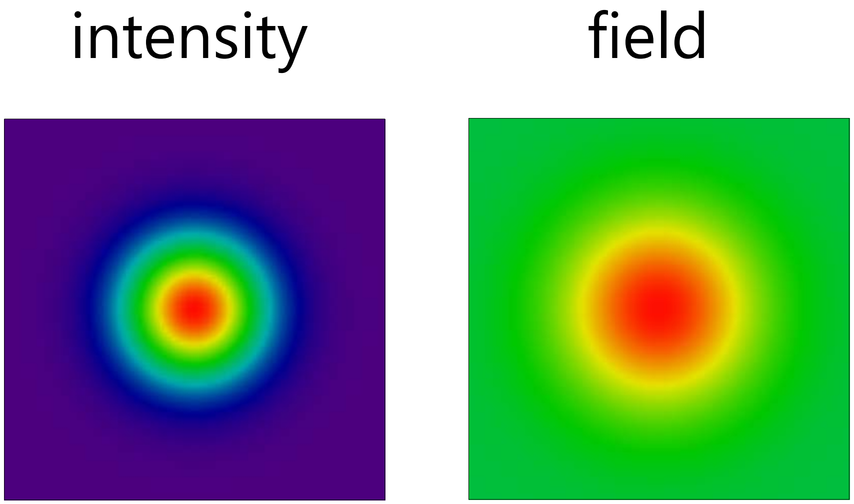
An example problem

Separating overlapping beams

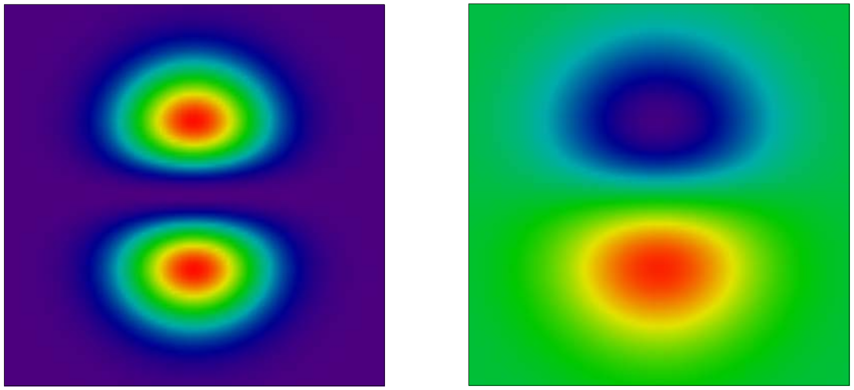
Example - Separating overlapping beams

Suppose we have two different (orthogonal) beams

- e.g., from an optical fiber
  - such as
    - a “single bump” beam



- and
  - a “two bump” beam



Example - Separating overlapping beams

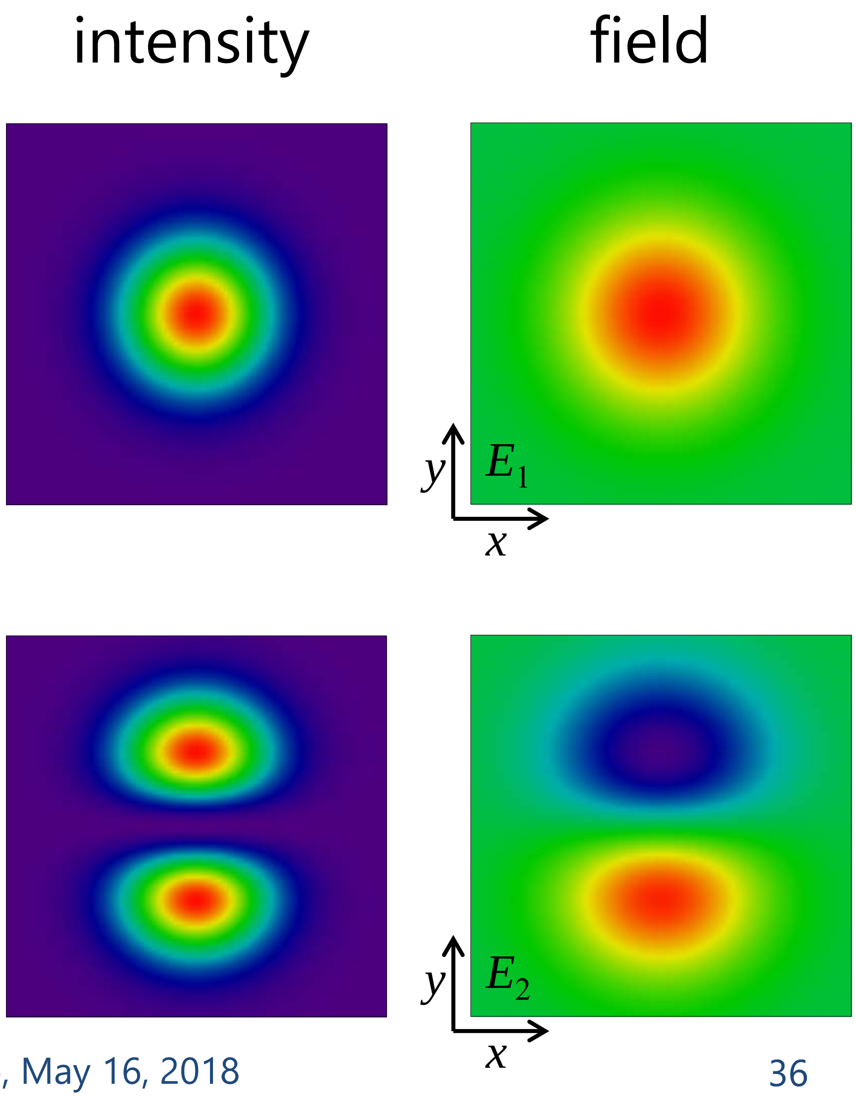
Mathematically,

- two (non-zero) beams are "orthogonal" if

$$\iint \mathbf{E}_1^*(x,y)\cdot\mathbf{E}_2(x,y)\,dxdy = 0$$

Here, the product of the

- single-bump beam and the two-bump beam
  - would be negative in the top half
  - but positive in the bottom half
    - so the resulting integral would be zero



Example - Separating overlapping beams

If both of these beams emerge simultaneously from the fiber

- how can we separate them
  - for example to different fibers
    - without loss?

“loss-less” mode separator

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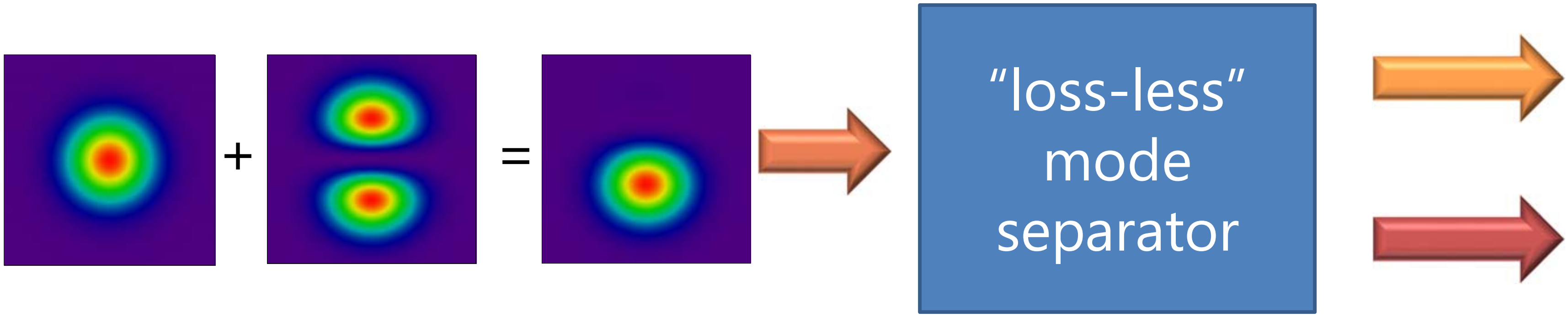
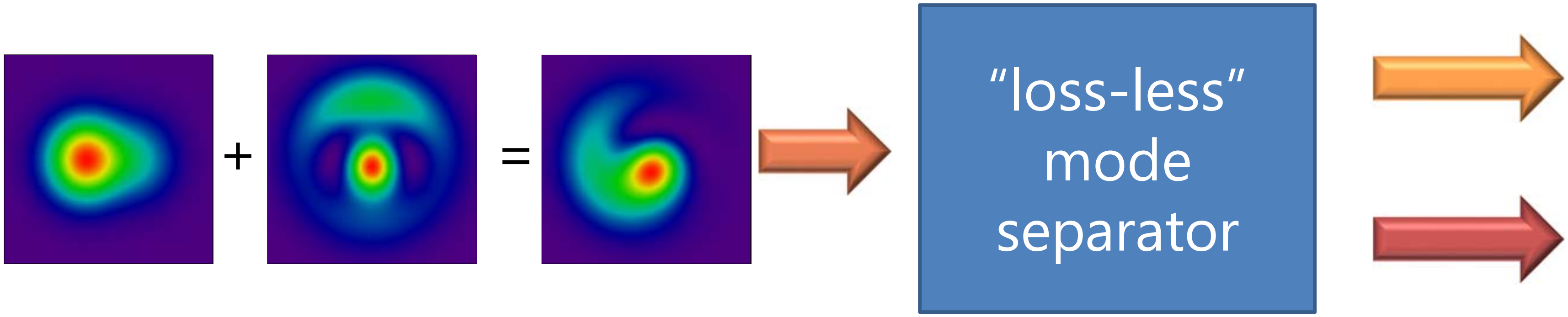


In situations with
- fixed
- highly symmetric beams
  - good specific low-loss separation solutions are known

Example - Separating overlapping beams

But for general cases

- of lower symmetry and/or higher complexity
  - or where the beams change in time
    - general solutions have not been known

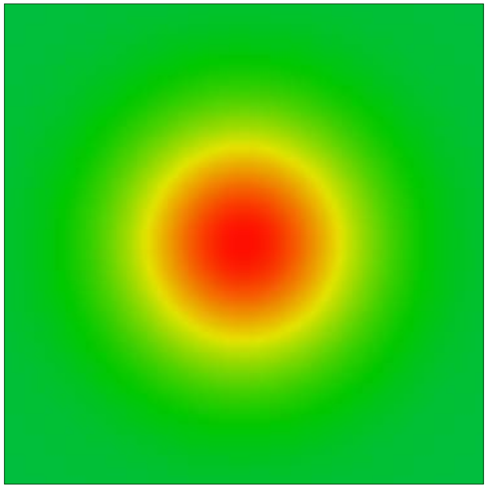


“loss-less” mode separator

Dividing the beam into “patches”

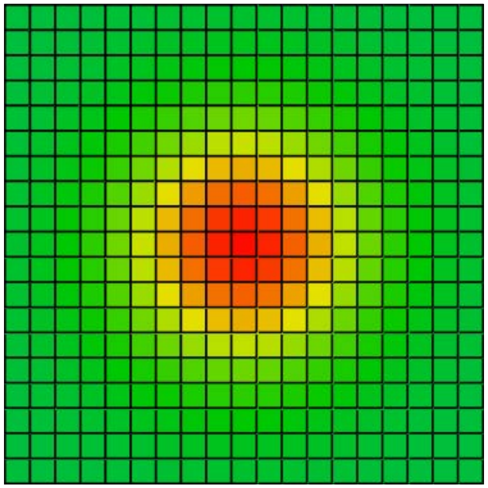
We can approach the beam-separation problem

- by presuming it will be good enough
  - to imagine that we can divide the beam up
    - into a finite number of “patches”



Dividing the beam into “patches”

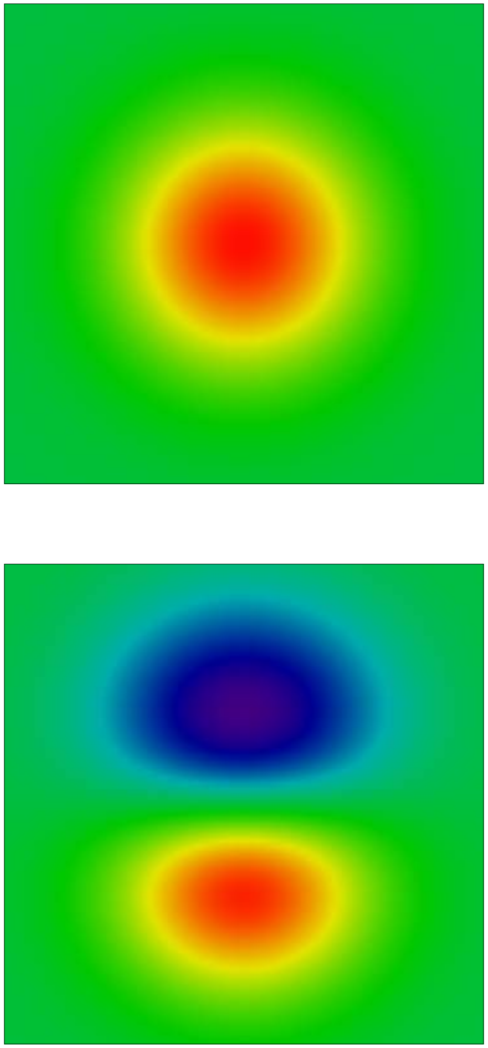
- We can approach the beam-separation problem
  - by presuming it will be good enough
    - to imagine that we can divide the beam up
      - into a finite number of “patches”
- We treat each of these patches
  - as if it was approximately uniform
    - in intensity and
      - in phase
- At least with a sufficiently large number of patches
  - this could be a good enough approximation
    - and “sampling loss” may be small



Dividing the beam into “patches”

Even relatively small numbers of patches

- are sufficient to distinguish beams of low or moderate complexity



Dividing the beam into “patches”

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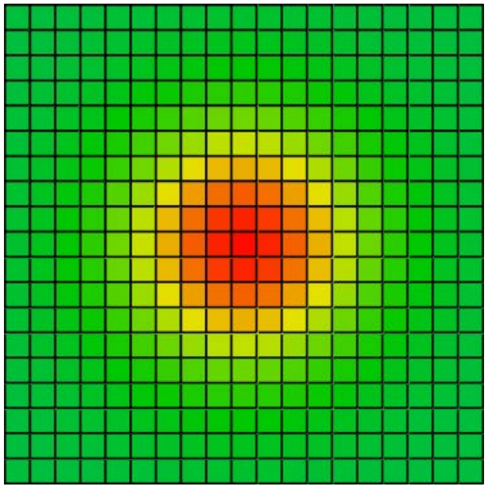

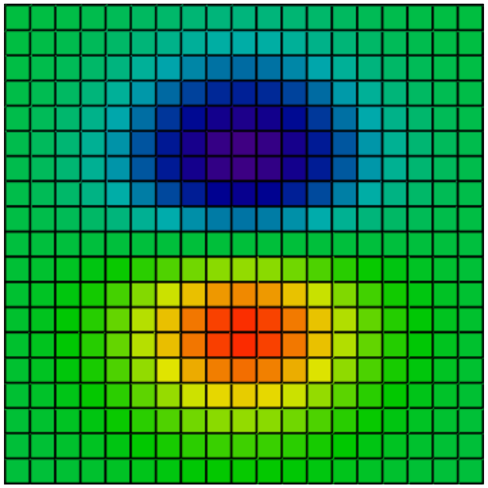

Dividing the beam into “patches”

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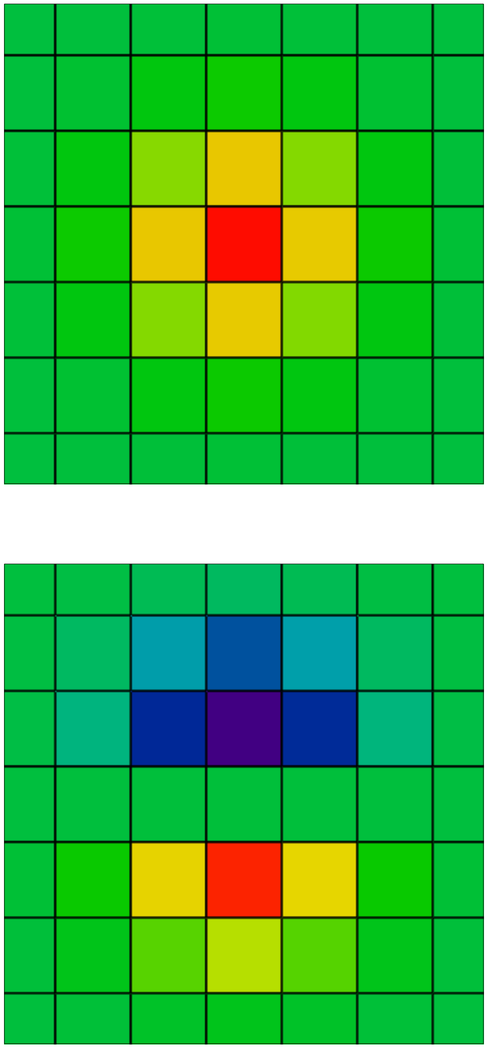
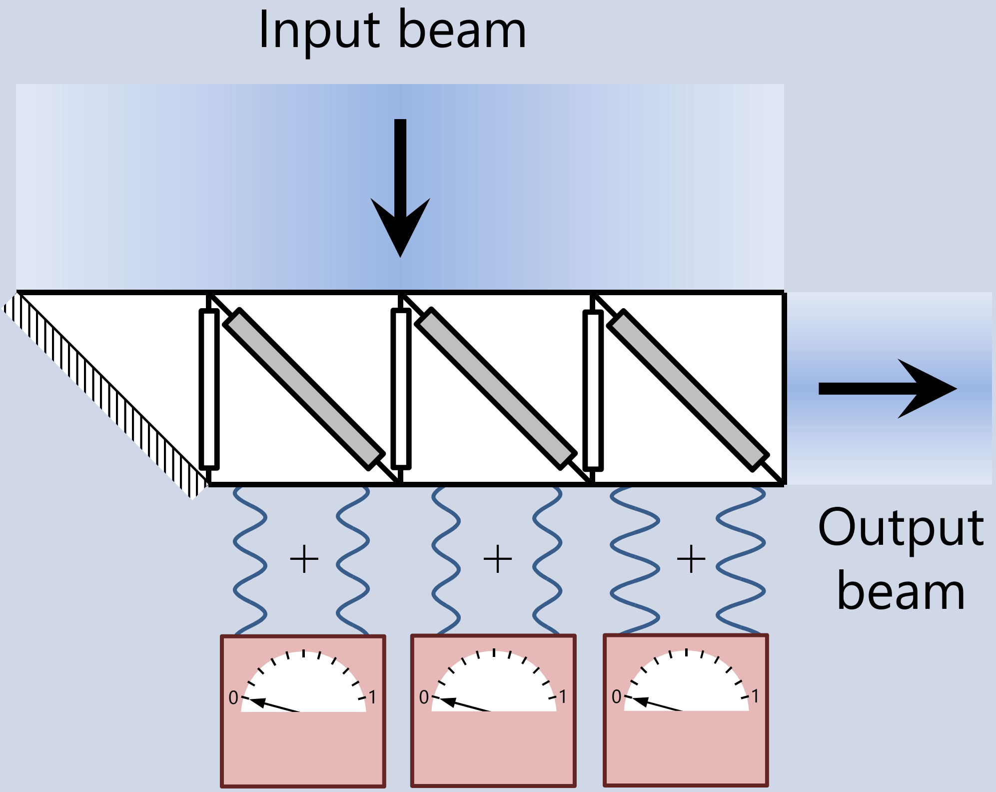
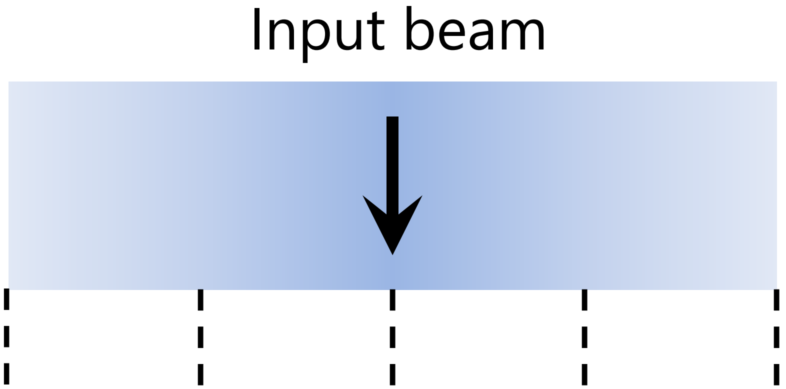




The first step …

A self-aligning universal beam coupler

Coupling an arbitrary input beam

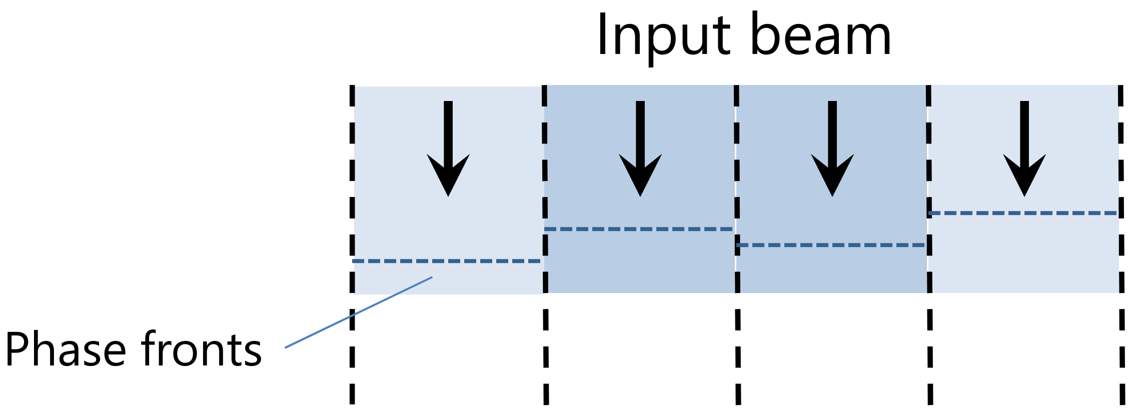


“Self-aligning universal beam coupler,” Opt. Express **21**, 6360-6370 (2013)

For illustration

- suppose, for simplicity, that
  - an arbitrary input beam can be adequately described by splitting it into 4 sections

Coupling an arbitrary input beam



"Self-aligning universal beam coupler," Opt. Express **21**, 6360-6370 (2013)

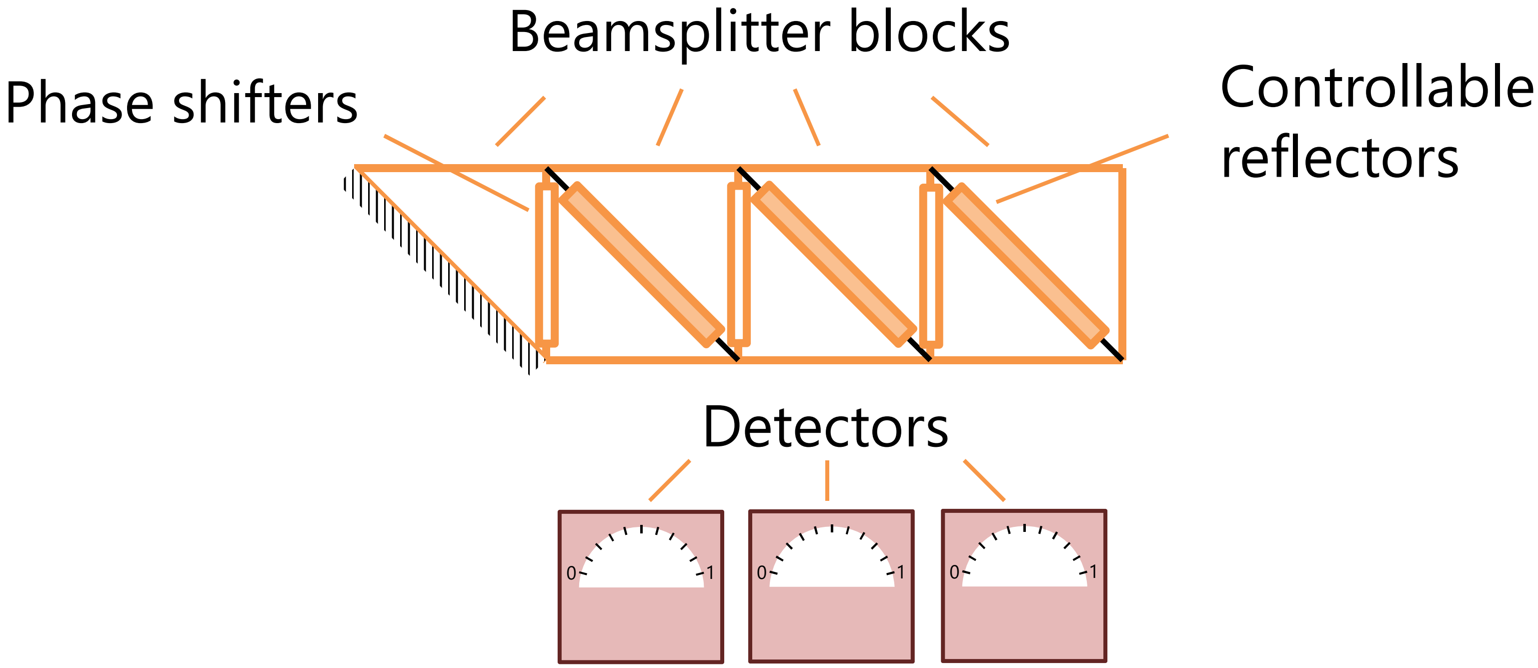
For illustration

- suppose, for simplicity, that
  - an arbitrary input beam can be adequately described by splitting it into 4 sections
    - each approximately uniform in intensity and "flat" in phase

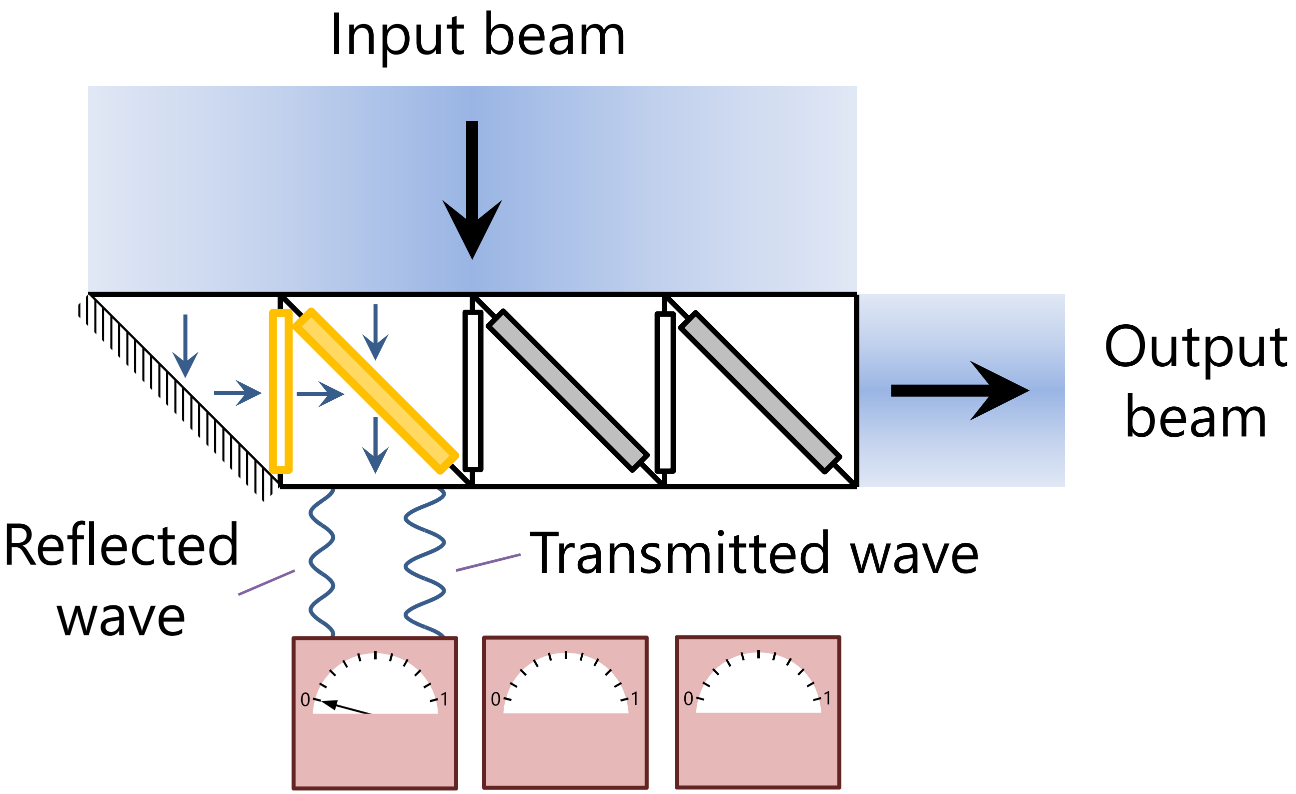
For simplicity, neglect diffraction for the moment

- assuming each of these sections will propagate as a "square" section of the beam

Self-aligning beam coupler



Self-aligning beam coupler



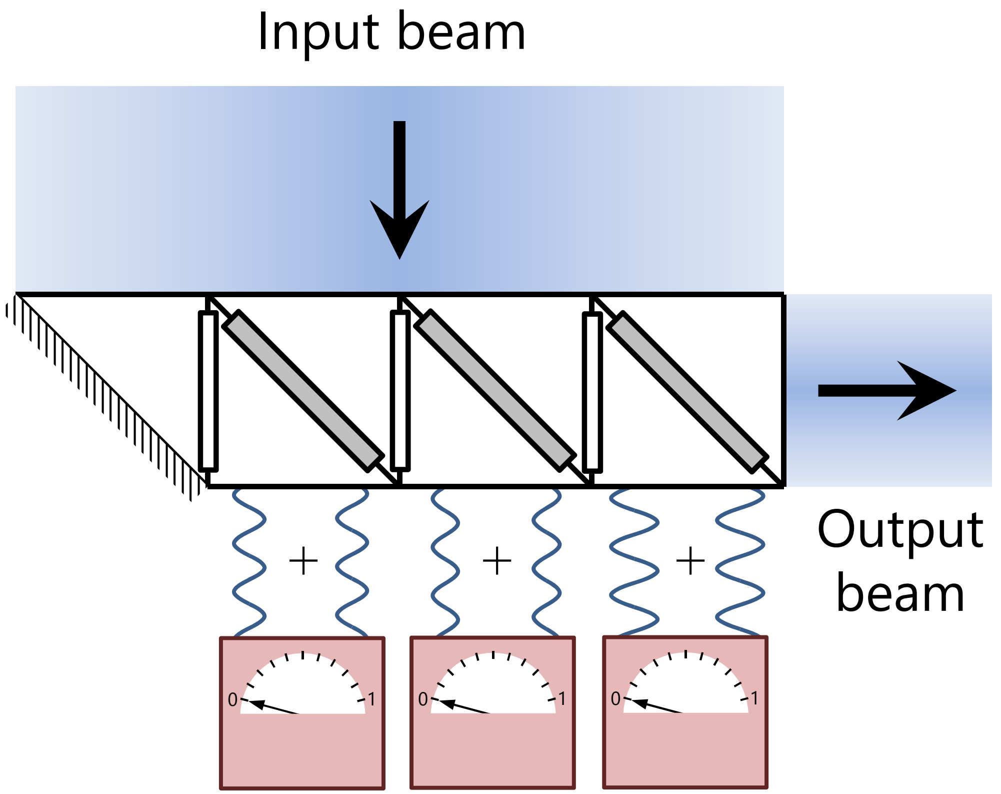
Adjust phase shifter in first block to minimize power in first detector

- Adjust reflectivity in first block to minimize power again in first detector

Repeat for each block

- Leaves no power in detectors, all input power in output beam

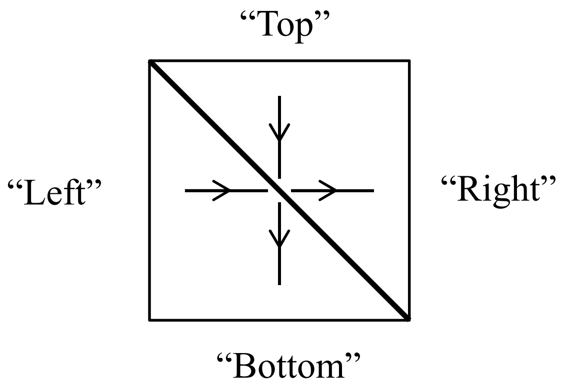
Self-aligning the beam coupler



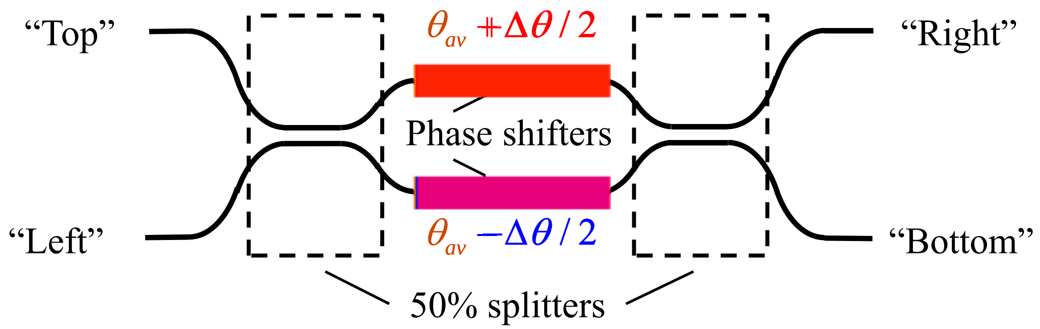
Now all the input beam power is coupled to the output beam

- Regardless of the form of the input beam
  - And without any calculation or detailed calibration of devices

Mach-Zehnder interferometer as controllable reflector and phase shifter



Beam splitter



Waveguide Mach-Zehnder interferometer

A Mach-Zehnder interferometer functions both as a controllable "reflector"

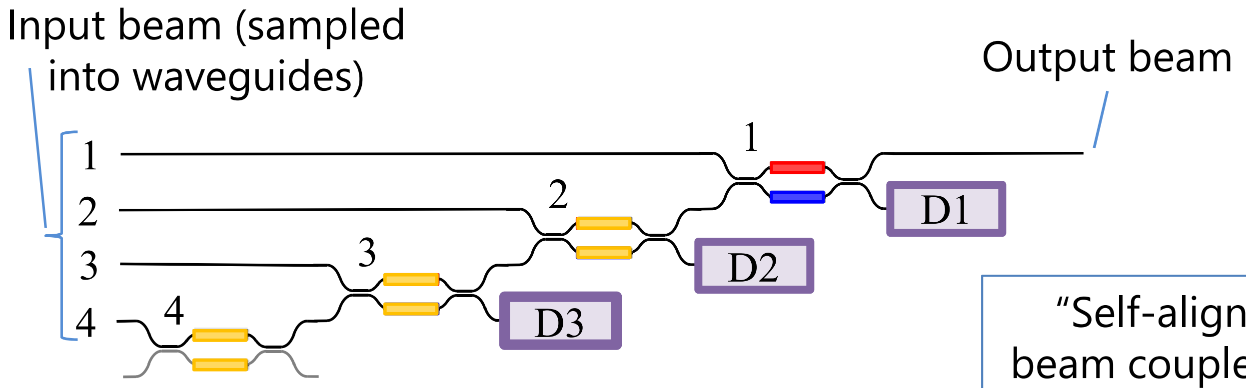
- Using differential drive $\Delta\theta$ of the two phase shifter arms

And as a controllable phase shifter

- Using common mode drive θ_{av} of the two phase shifter arms

To control amplitude and phase of the outputs

Mach-Zehnder self-aligning implementations



"Self-aligning universal beam coupler," Opt. Express **21**, 6360-6370 (2013)

Adjust phase in device 4 to minimize power on D3

Adjust split ratio in device 3 to minimize power on D3

Adjust phase in device 3 to minimize power on D2

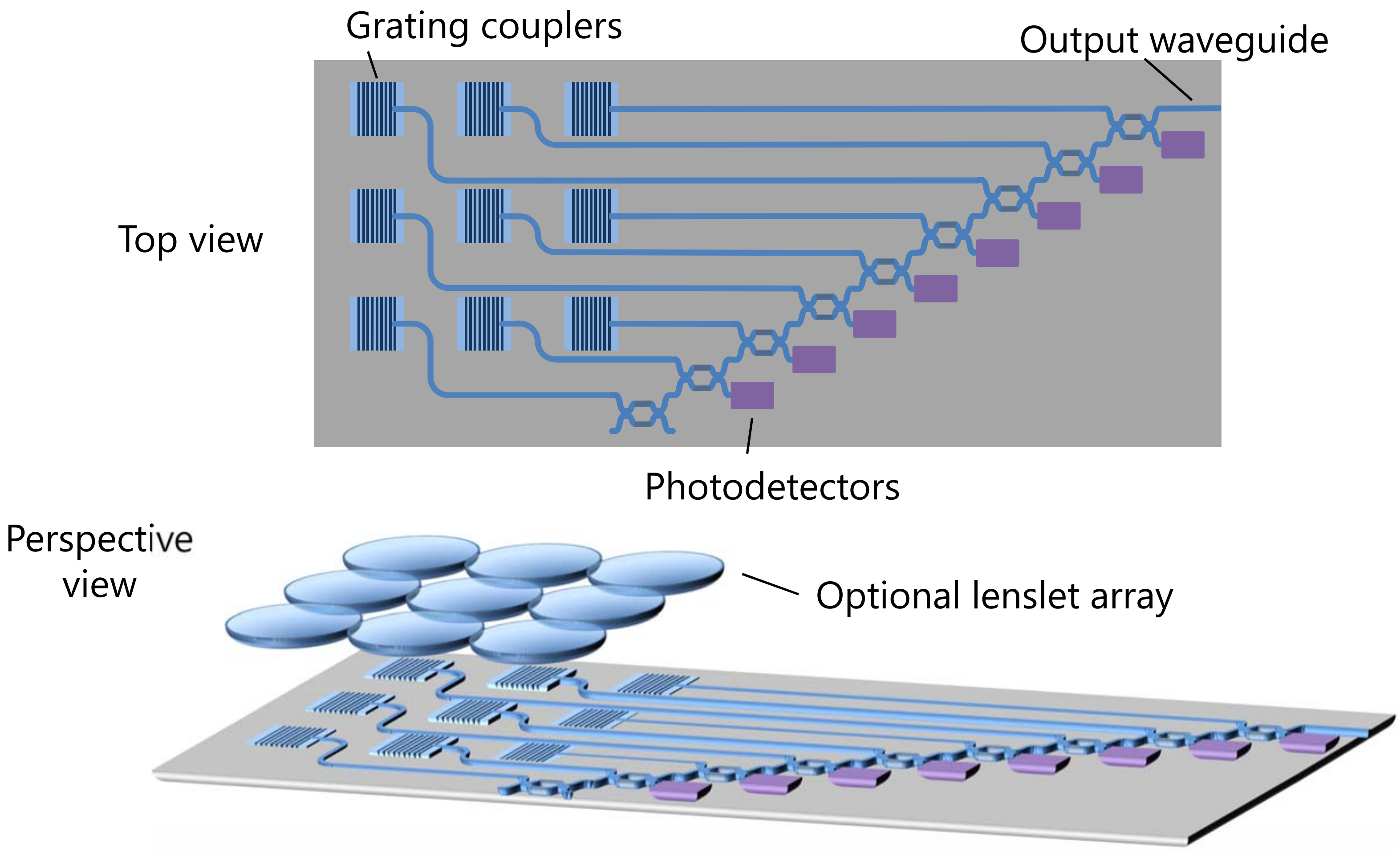
Adjust split ratio in device 2 to minimize power on D2

Adjust phase in device 2 to minimize power on D1

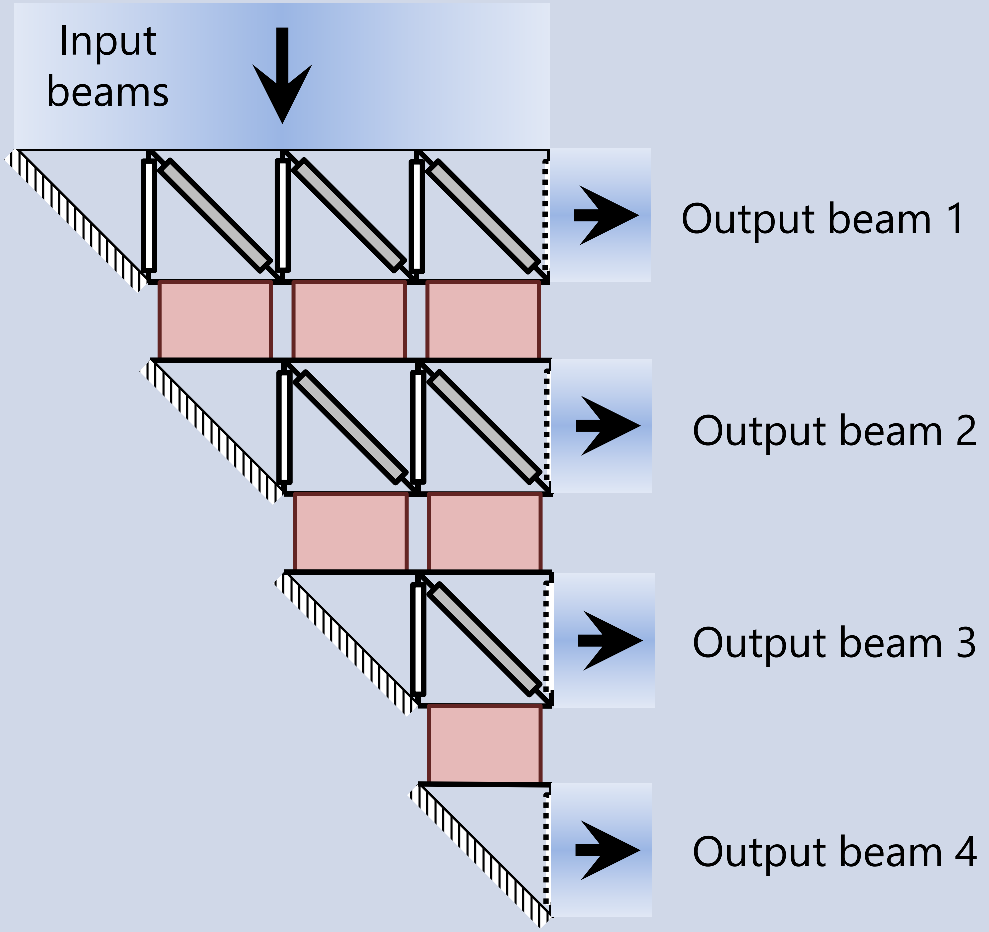
Adjust split ratio in device 1 to minimize power on D1

All power from the input waveguides now in output beam

Mach-Zehnder self-aligning implementations



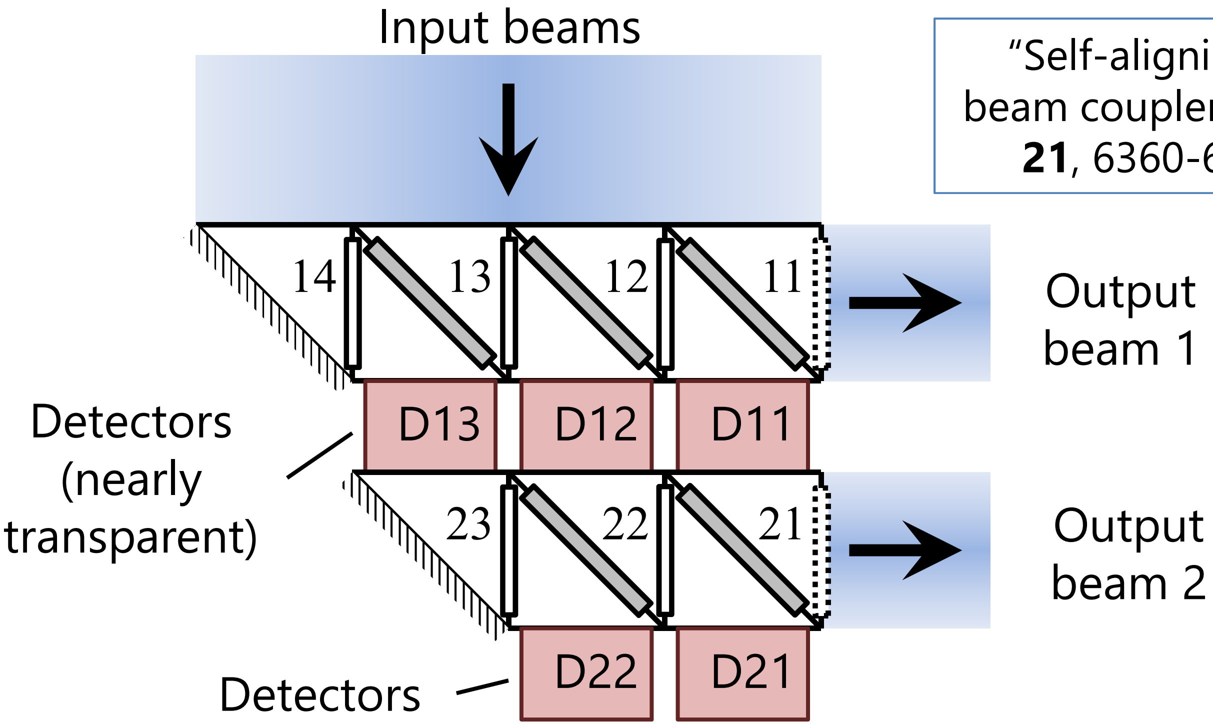
Grating couplers would allow us to couple a free-space beam to a Mach-Zehnder implementation of the device



The second step …

Separating multiple orthogonal beams

Separating multiple orthogonal beams



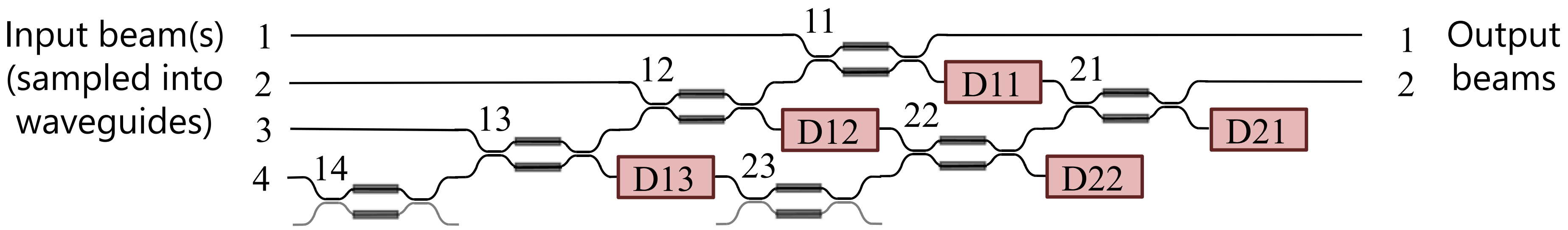
"Self-aligning universal beam coupler," Opt. Express **21**, 6360-6370 (2013)

Once we have aligned beam 1 using detectors D11 – D13

- an orthogonal input beam 2 passes through the nearly transparent detectors to the second row
  - where we can self-align it using detectors D21 – D22

separating two overlapping orthogonal beams to separate outputs

2 beam Mach-Zehnder implementation



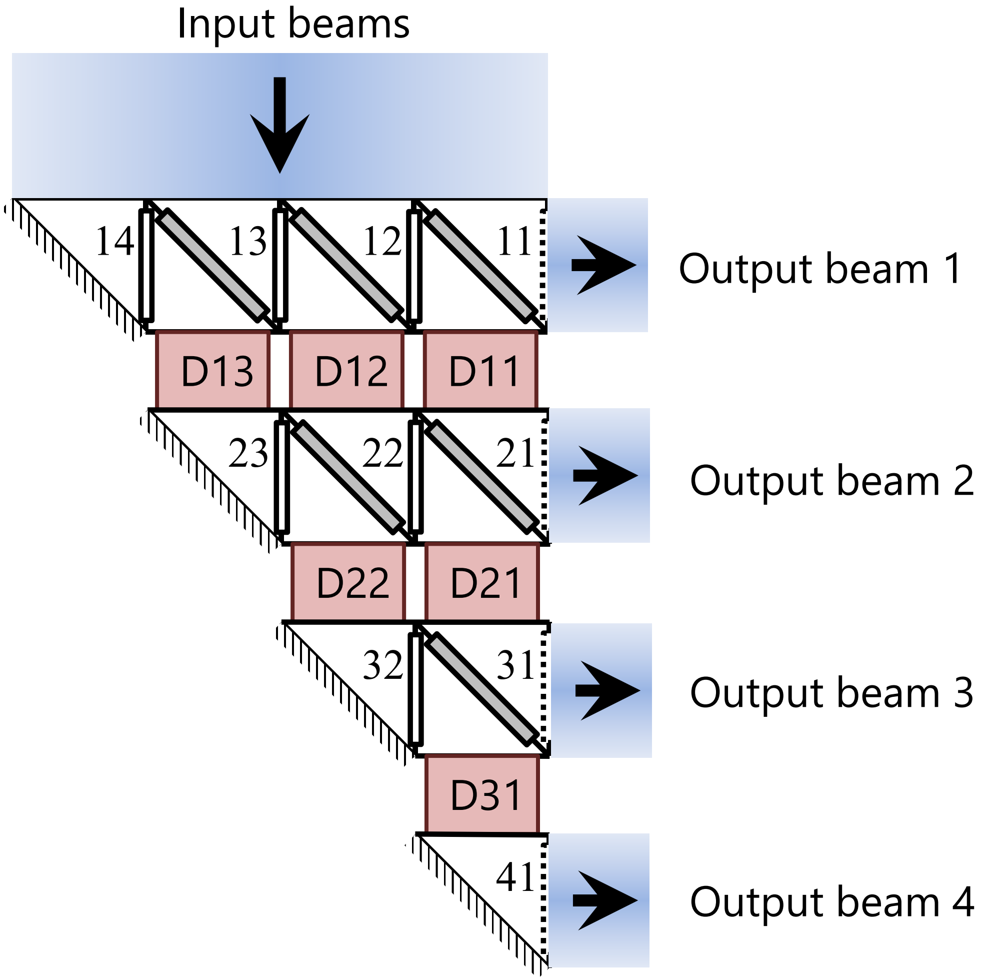
D11, D12, D13 are mostly-transparent detectors

Since alignment and re-alignment need not be performed at data-rate speeds

only need small signals from the detectors

Many ways of making such mostly-transparent detectors

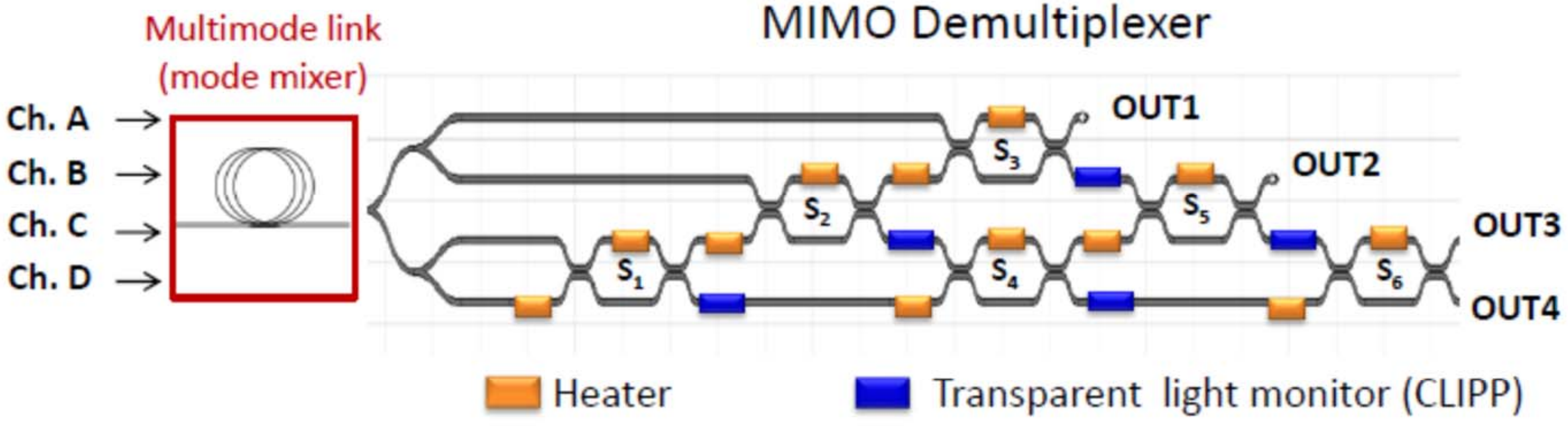
Separating multiple orthogonal beams

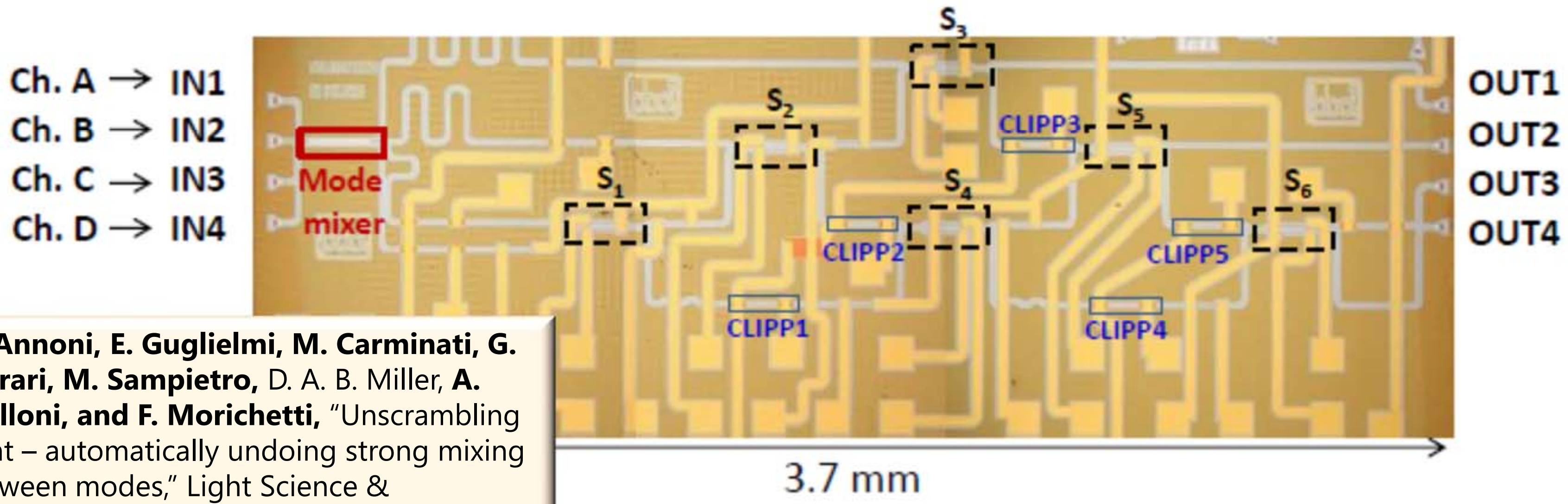


Adding more rows and self-alignments

- separates a number of orthogonal beams
  - equal to the number of beam "segments"
    - here, 4

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)

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

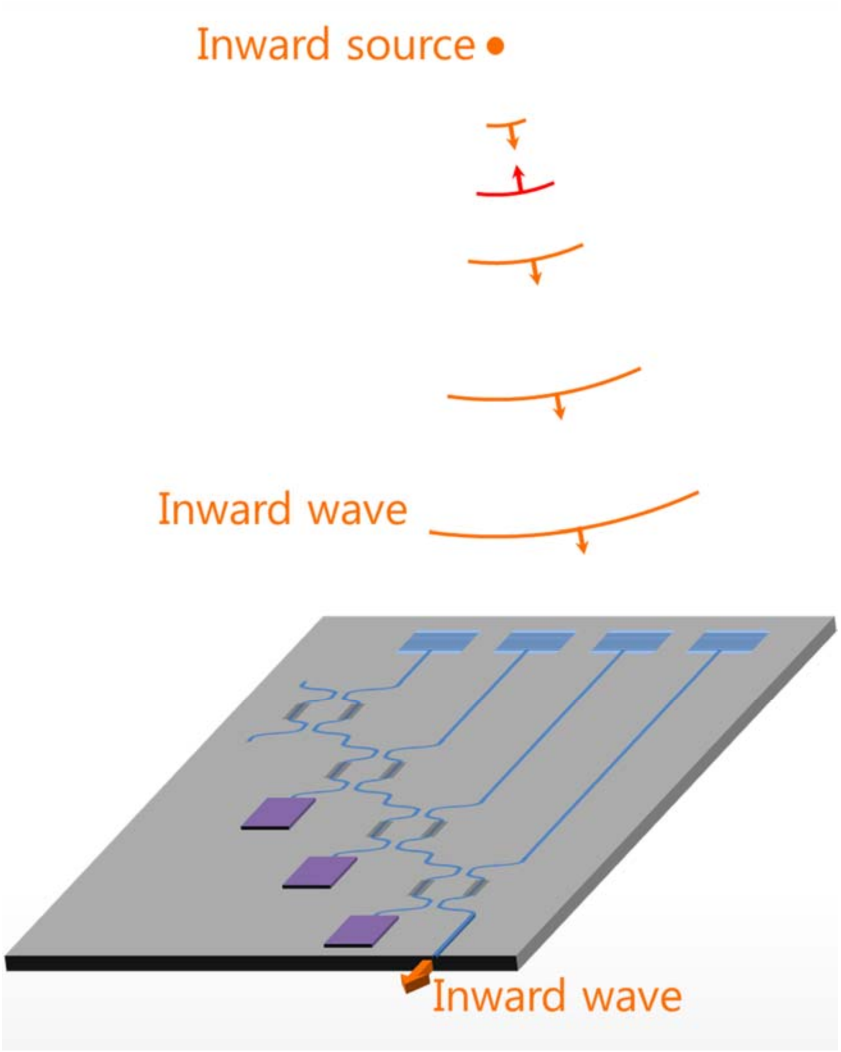
Si chip fabricated
by CEA-Leti

Extensions – tracking a source

Optimize reception of a wave from a source

- An adaptive front end for a sensing system
  - e.g., finding and/or tracking a source

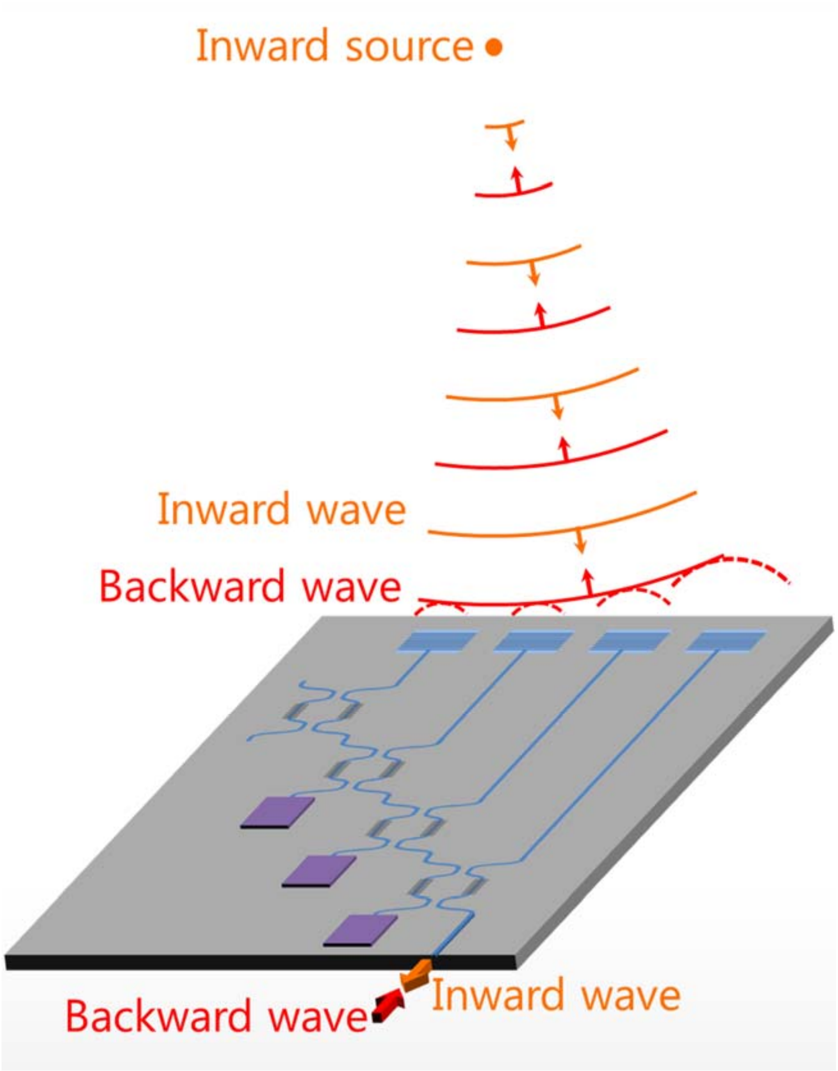
“Establishing optimal wave communication channels automatically,” J. Lightwave Technol. 31, 3987 – 3994 (2013)



Extensions – tracking a source

- Optimize reception of a wave from a source
  - An adaptive front end for a sensing system
    - e.g., finding and/or tracking a source
- Creating an optimum backwards channel to a source
  - for communications
    - or powering

"Establishing optimal wave communication channels automatically," J. Lightwave Technol. 31, 3987 – 3994 (2013)

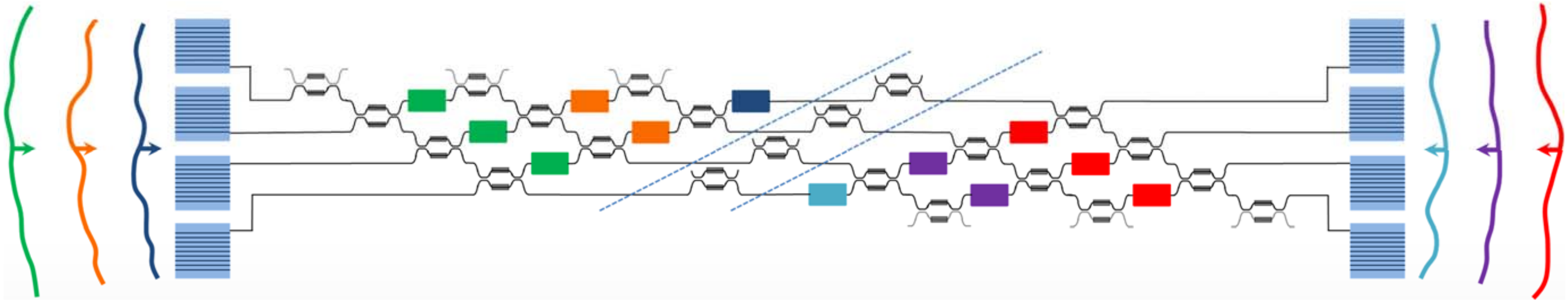


Extensions – self-stabilizing optical systems

Keep "training beams" on all the time in the background
  - "key" each training beam, e.g., with an amplitude modulation
    - at a different frequency for each beam
      - photodetector rows respond only to "keyed" signals

With the local electronic feedback loops enabled in sequence
  - the system will stabilize itself
    - to continue implementing the trained function

E.g., arbitrary transforms for optical and/or quantum processing



input training beams

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

output training beams

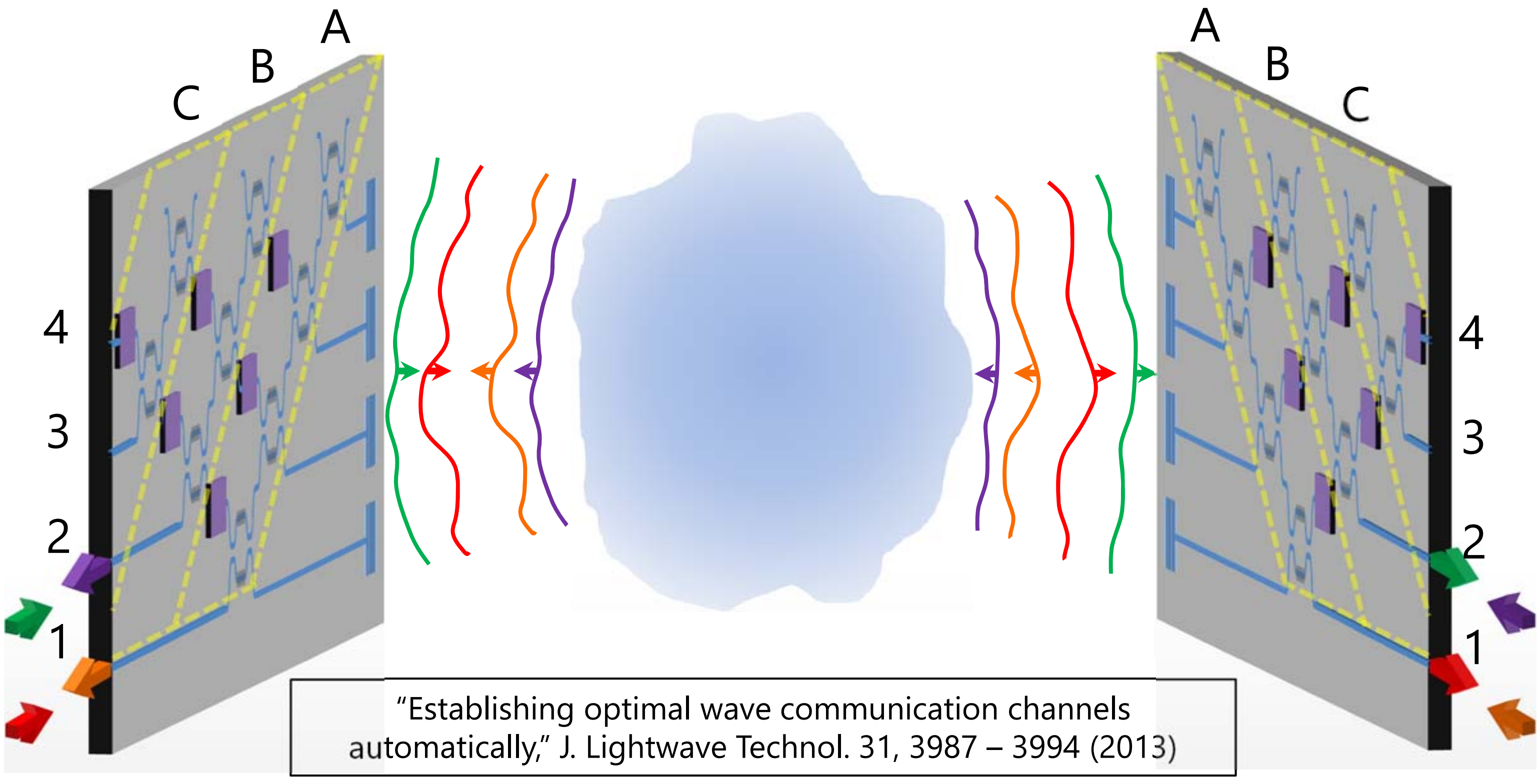
Extensions – optimal channels

Iterating back and forward between the two sides

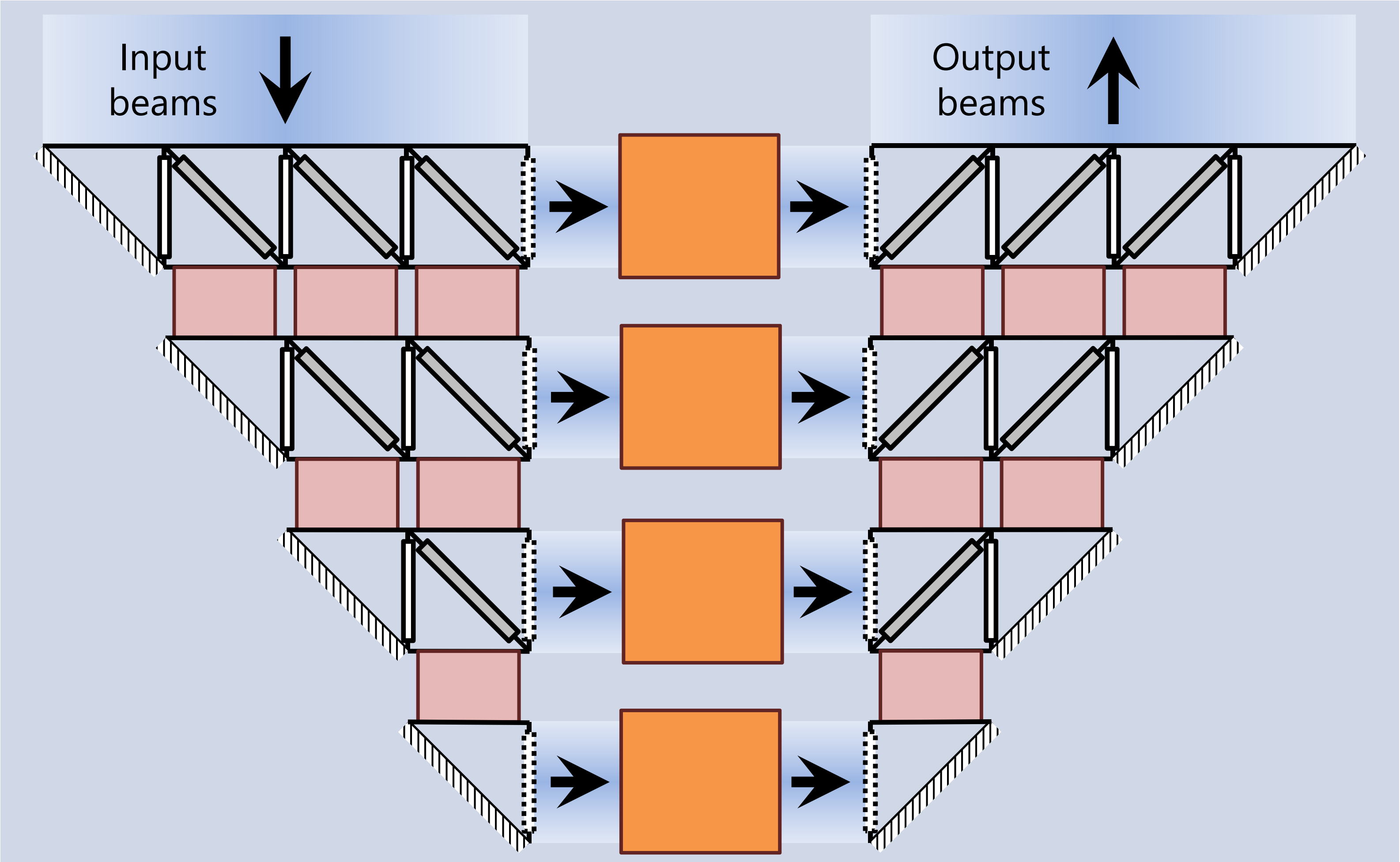
- Finds the optimal orthogonal channels through any medium

Physically, performs the singular value decomposition of the optics

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



"Establishing optimal wave communication channels automatically," J. Lightwave Technol. 31, 3987 – 3994 (2013)

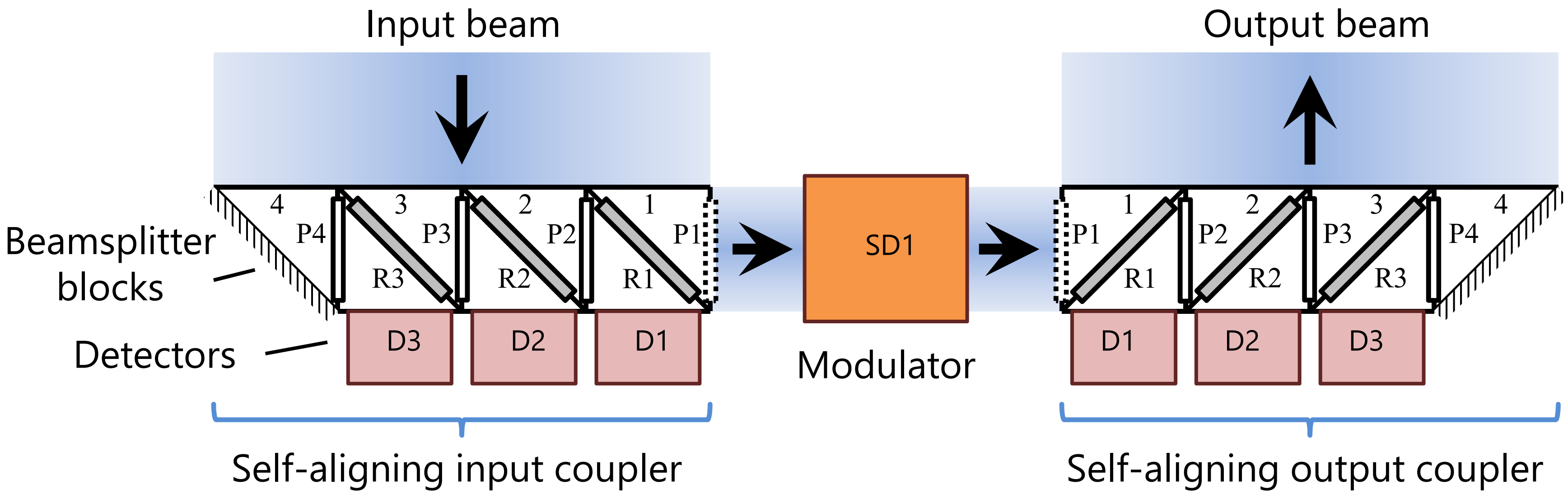


The third step …

A self-configuring universal spatial device

Politecnico di Milano, May 16, 2018

Arbitrary mode converter

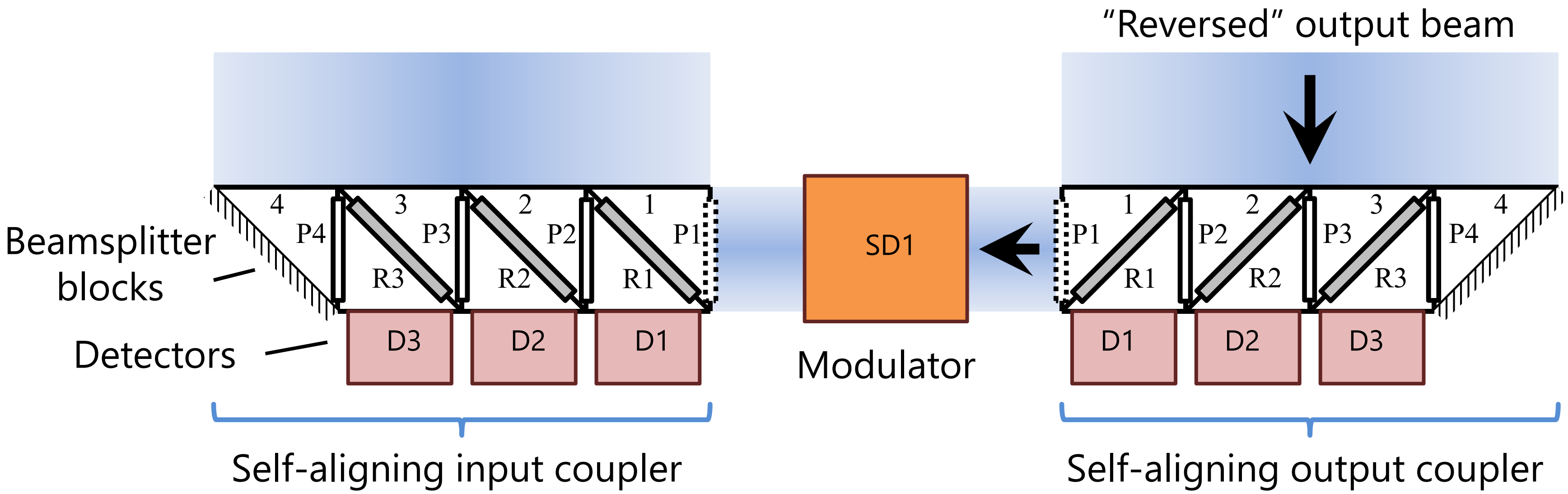


Exploit two back-to-back self-aligning universal beam couplers

Self-align input coupler by shining in beam of interest and adjusting using local feedback loops as before

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

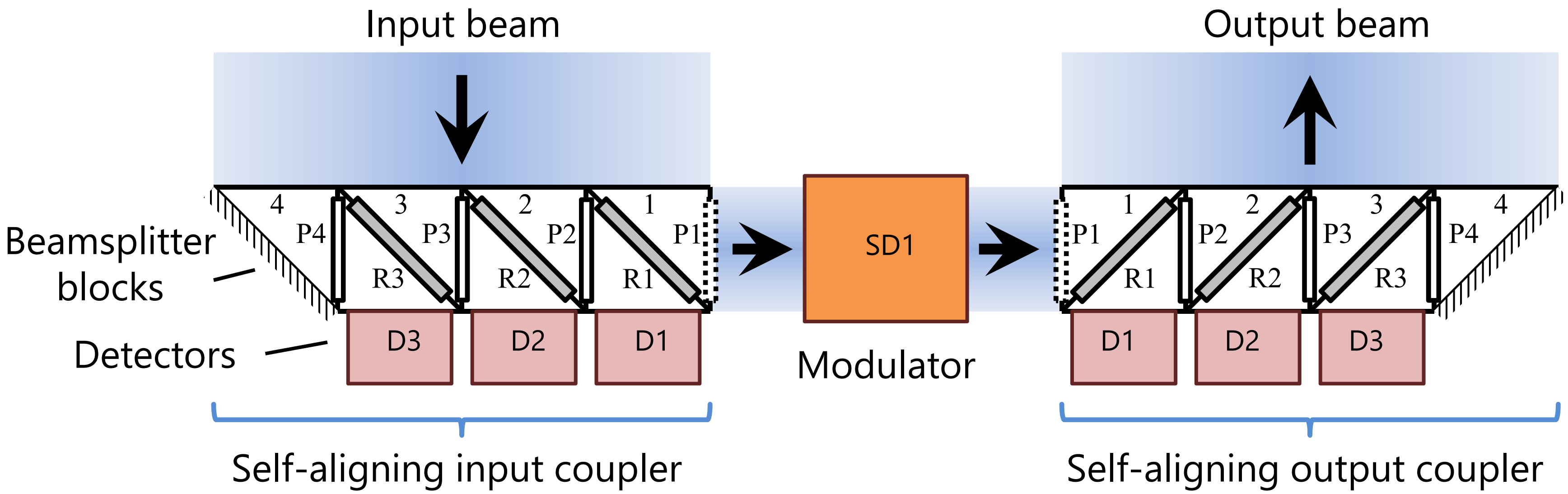
Arbitrary mode converter



Self-align the output coupler

- shining desired output beam *backwards* into the output coupler
  - technically, the phase conjugate of the desired output beam
- And adjusting using local feedback loops as before
  - But now in the *output* coupler

Self-configuring linear spatial device



Now any single desired input beam

is converted to

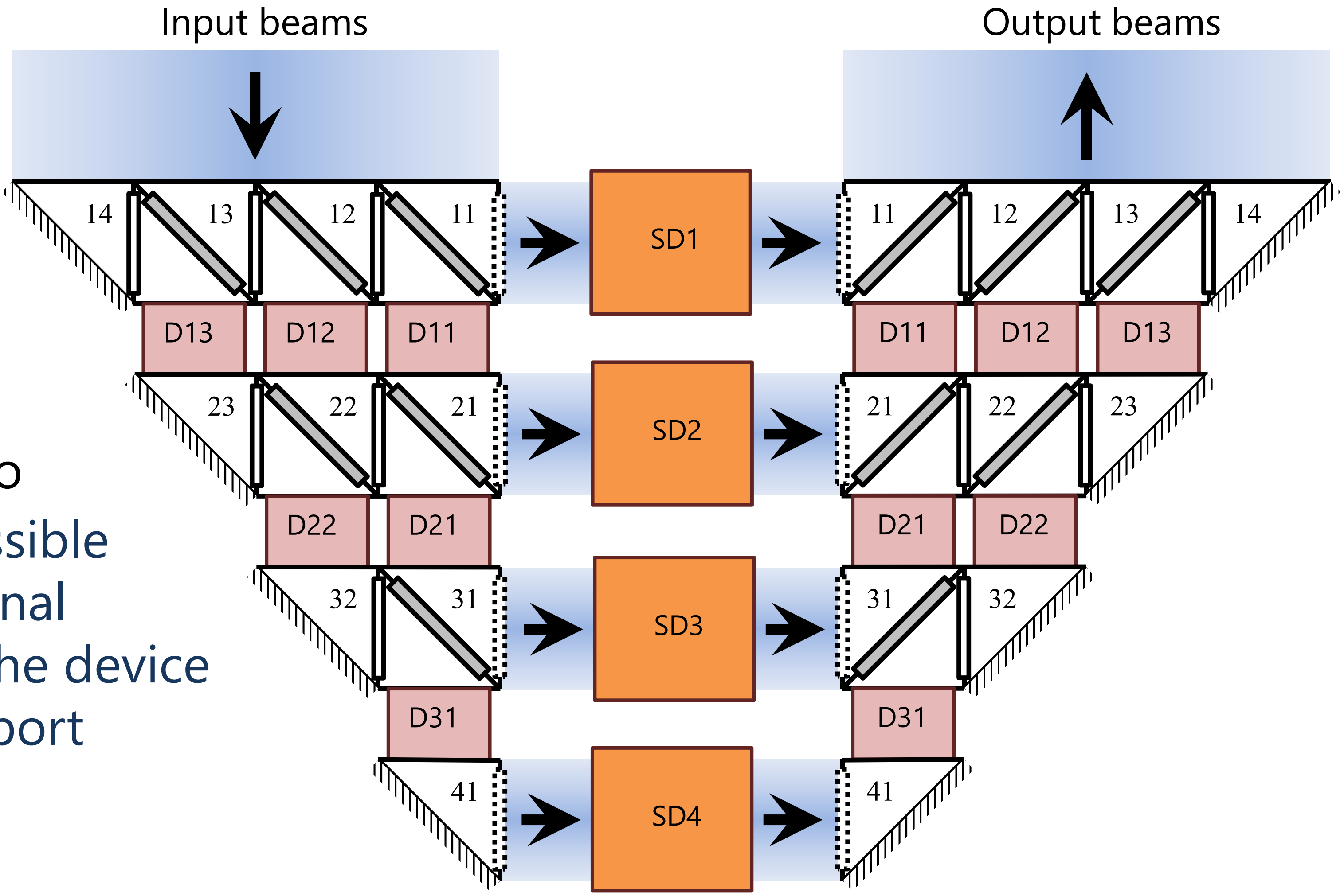
any single desired output beam

with no calculations

by training the device with the desired beams

Can also adjust modulator to give desired coupling strength

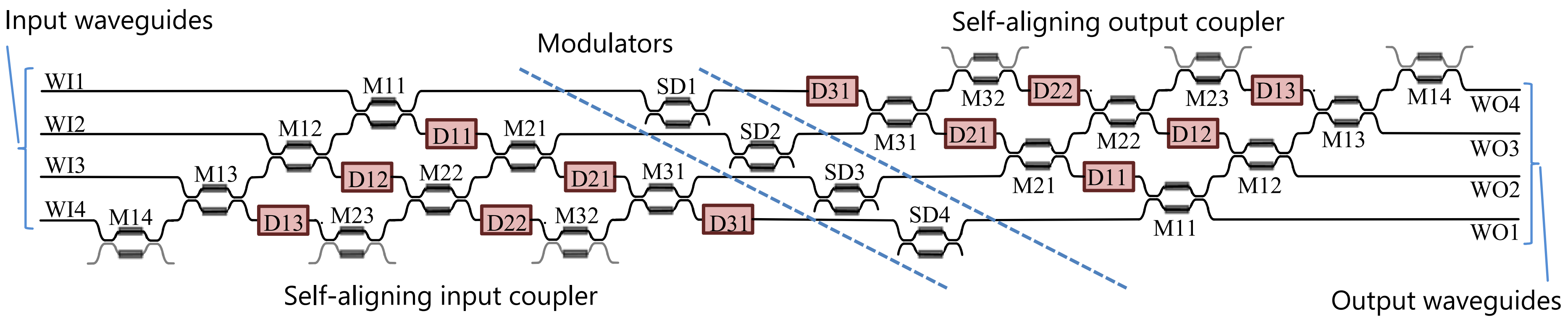
General multiple mode converter



Can extend to

- all the possible orthogonal beams the device can support

Mach-Zehnder implementation



Input waveguides

Modulators

Self-aligning output coupler

Self-aligning input coupler

Output waveguides

Same concept can be implemented in a planar Mach-Zehnder form

- No crossing waveguides required

Example here has the output order flipped for compactness

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

Describing an arbitrary linear optical component

Any linear optical component can be described by a linear "device" or scattering operator D

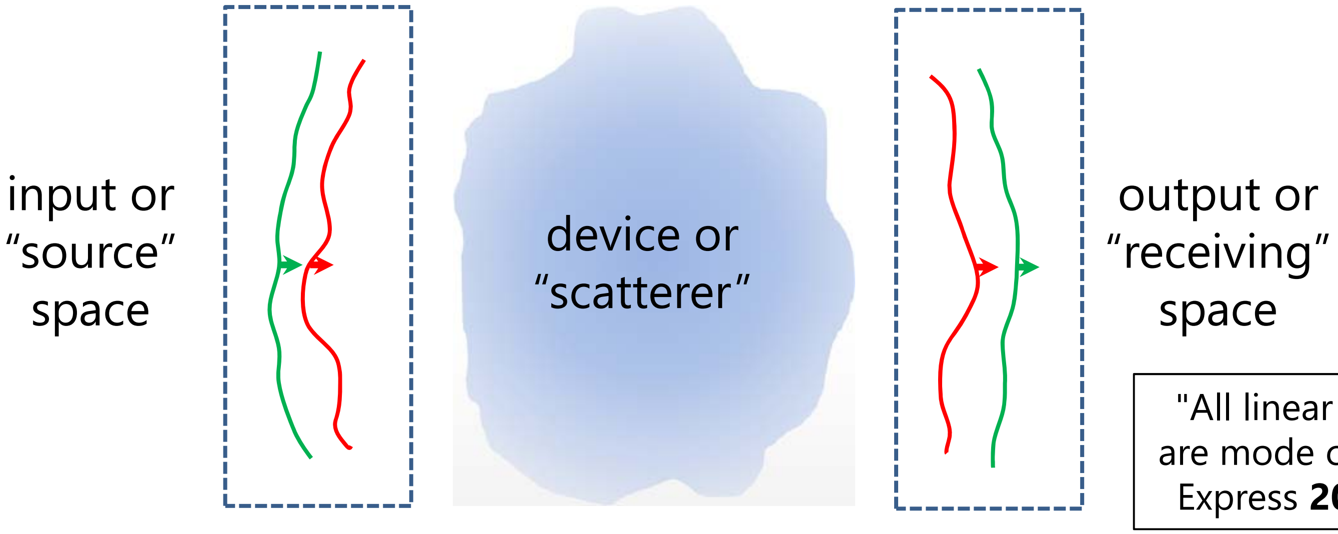
and we can perform the singular value decomposition (SVD)

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

U and V are unitary operators and D_{diag} is a diagonal operator

If we can emulate any SVD for given input and output spaces

then we can make any linear optical device for those spaces



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

Formal mathematics – singular value decomposition

These configurations implement the singular value decomposition

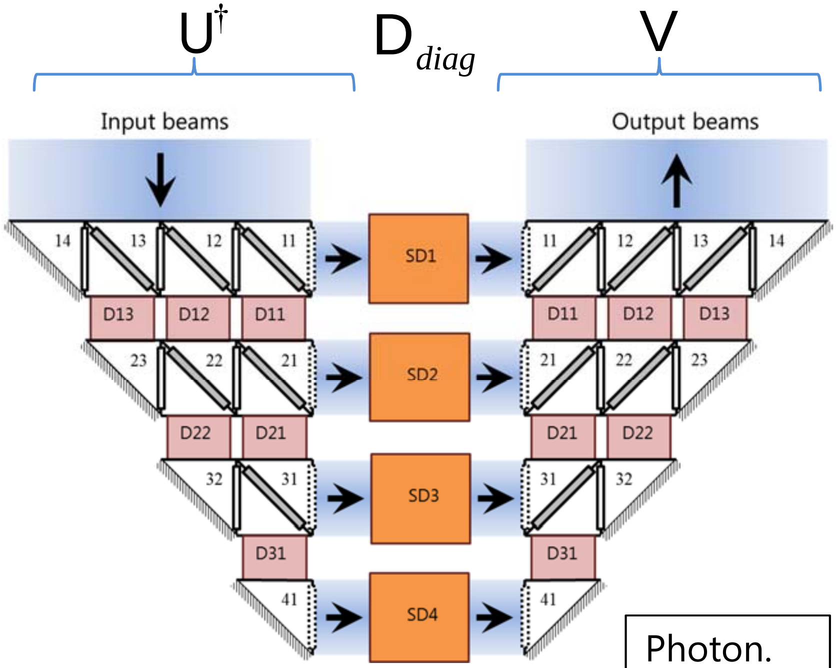
with full generality

so we can design and make

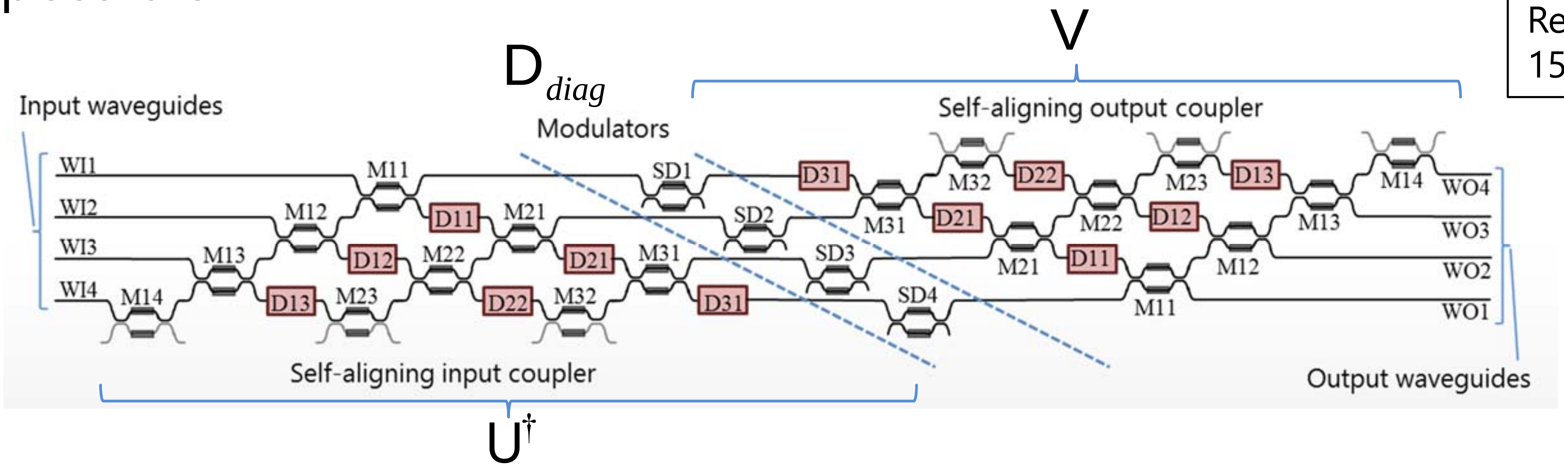
any linear optical component

for these input and output spaces

Proves any linear optical component is possible



Photon. Res. **1**, 1-15 (2013)



Conclusions

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dabm@ee.stanford.edu

DM, JLT **35**, 343 (2017)

J. M. Kahn and DM, Nat. Phot.11, 5 (2017)

- Novel low-energy optoelectronics, together with photodetectors right beside transistors
  - allow optoelectronics at 10 fJ or even 1 fJ levels
    - and can eliminate 100fJ/bit – pJ/bit receiver power dissipation
- Adding free-space optical arrays and silicon photonics as an interposer
  - allow us to eliminate the time-multiplexing circuitry
    - so we can go from 1 – 10 pJ/bit to 10 – 100 fJ/bit
- New algorithms and designs for interferometer meshes
  - allow us to exploit the silicon photonics complexity
- Applications in
  - communications, sensing
  - signal processing and computing
  - linear optical quantum circuits
- New classes of self-configuring and self-optimizing optics
  - adaptable, manufacturable, complex optics

Conclusions

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If you can think of an linear optical device
- at least for one wavelength
  - there is a way of designing it
    - and making it (if it is not too complicated)
      - with interferometer meshes
        - which can also design and stabilize themselves

Now is the time to have fun with this!
- Something new for silicon photonics
  - get funded
    - make these devices
      - get rich!

Self-configuring optics references

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

"Setting up meshes of interferometers – reversed local light interference method," Opt. Express 25, 29233-29248 (2017)

DM, L. Zhu, and S. Fan, "Universal modal radiation laws for all thermal emitters," PNAS 114, no. 17, 4336-4341 (2017)

Annoni et al., "Unscrambling light – automatically undoing strong mixing between modes," Light Science & Applications 6, e17110 (2017)

Wilkes et al., "60 dB high-extinction auto-configured Mach–Zehnder interferometer," Opt. Lett. 41, 5318-5321 (2016) "Perfect optics from imperfect components," Optica **2**, 747-750 (2015)

"Sorting out light," Science **347**, 1423-1424 (2015)

"Designing Linear Optical Components," Optics in 2013 Special Issue, Optics and Photonics News, December 2013, p. 38

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"Communicating with Waves Between Volumes – Evaluating Orthogonal Spatial Channels and Limits on Coupling Strengths," Appl. Opt. **39**, 1681–1699 (2000)

For an overview, including all these links, see http://www-ee.stanford.edu/~dabm/Selfalign.html