Programmable Optics for Novel Applications

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Collaborators

Stanford

- Groups of Shanhui Fan, Joe Kahn, Olav Solgaard
  - especially Annie Kroo, Paul-Alexis Mor, Sunil Pai, Charles Roques-Carmes, Carson Valdez, Marek Vlk

Politecnico di Milano

- Groups of Andrea Melloni, Francesco Morichetti, Marco Sampietro
  - especially Gabrielle Cavicchioli, Vittorio Grimaldi, Maziyar Milanizadeh, SeyedMohammad SeyedinNavadeh

NASA

- Group led by Rus Belikov
  - especially Eduardo Bendek, Kevin Fogarty, Rachel Morgan, Dan Sirbu

Glasgow

- Group of Martin Lavery
  - especially Aleksander Boldin

See also later talks in this Symposium

- Annie Kroo – Tuesday afternoon “Photonic Integrated Circuits for Edge Computation”
- Shanhui Fan – Wednesday afternoon “Process quantum states with waveguide meshes”

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What I will not talk about

A next generation of highly parallel free-space optical interconnects to

eliminate most of the energy of short (and longer) interconnects

which is most of the energy in datacenters

and scale to increased bandwidth density

A reasonable goal – **100 - 10 fJ/bit (total system energy) up to 10 m distance**

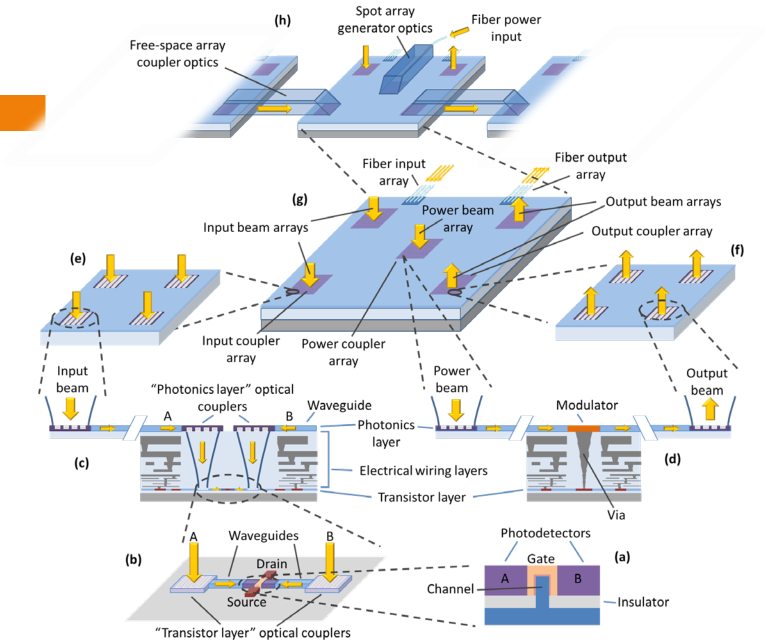
Note 10 fJ/bit implies only

10 mW power for 1 Tb/s interconnect bandwidth

Research on this has been completed some time ago

This awaits investment, development and commercialization

See also this video (OFC 21, dabm.stanford.edu/videos/#OFC2021)



"Straw man" system concept exploiting

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

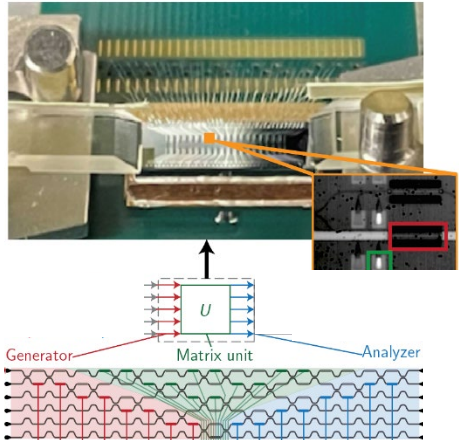
DM, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications: a Tutorial Review," IEEE/OSA JLT **35** (3), 343 (2017)

Mach-Zehnder interferometer meshes

Mach-Zehnder interferometer meshes in silicon photonics
- "universal" linear optical components

Many potential applications
- linear algebra of matrix multiplication and inversion
- optical applications
    - self-aligning beam couplers
    - separating overlapping orthogonal beams
    - modal spatial filtering
    - measuring amplitude and phase of optical fields
    - finding the best channels through an optical system
    - analyzing partially coherent light
    - programmable spectral filters

…



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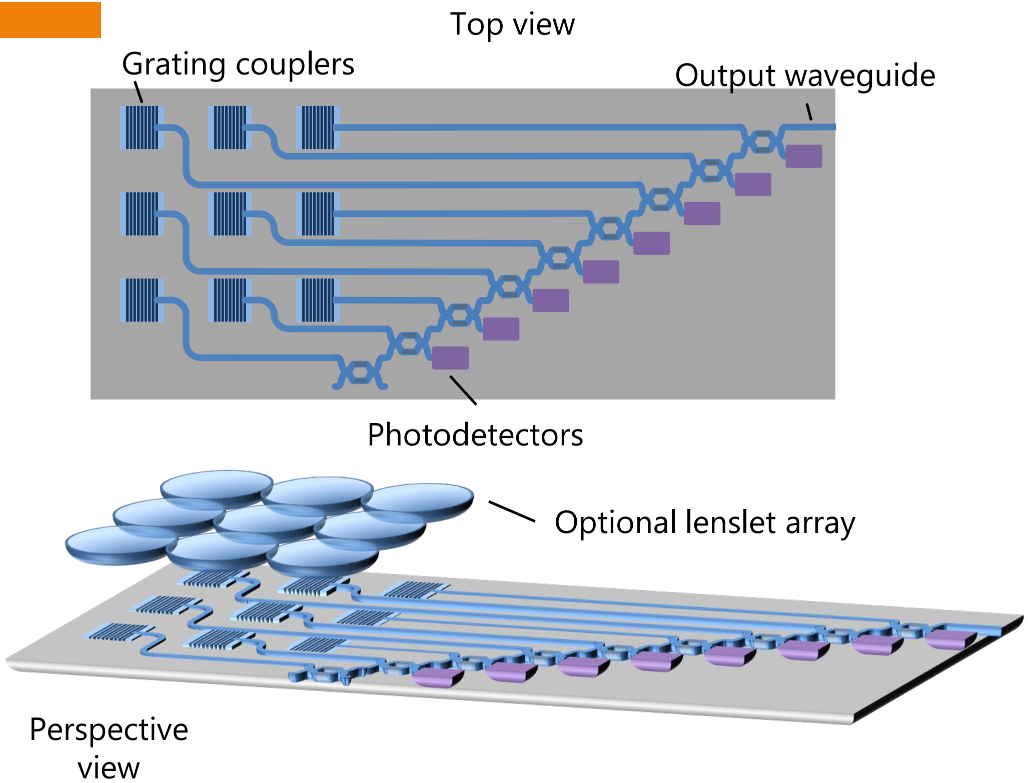
Self-aligning beam coupler

By progressively nulling out the power on each photodetector

- starting from the bottom of the line of Mach-Zehnder interferometers
- and working up
  - we can automatically couple all the power in the input couplers to a single output
  - just by successive single-parameter optimizations

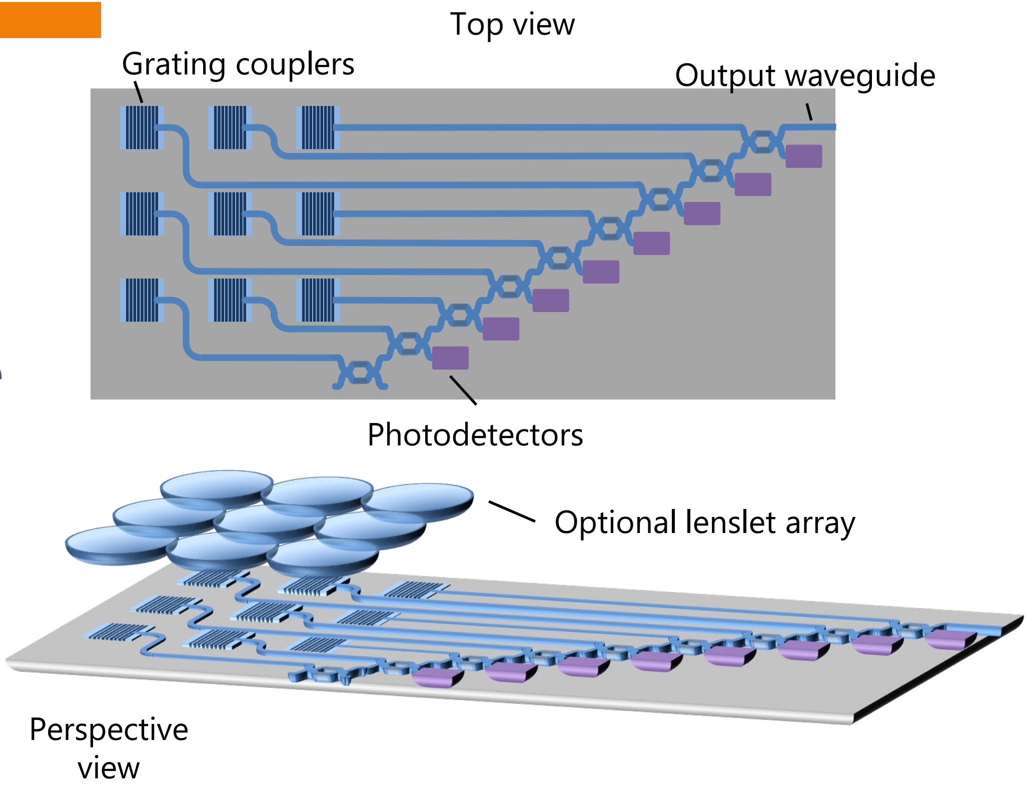


"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

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)

Separating beams with interferometer meshes

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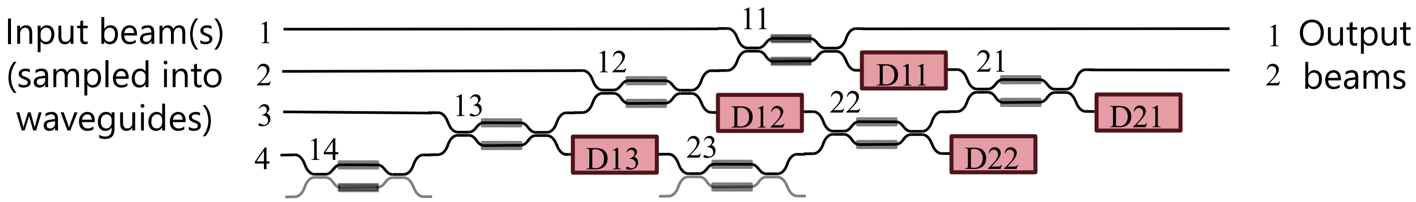
Separating multiple orthogonal beams



"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

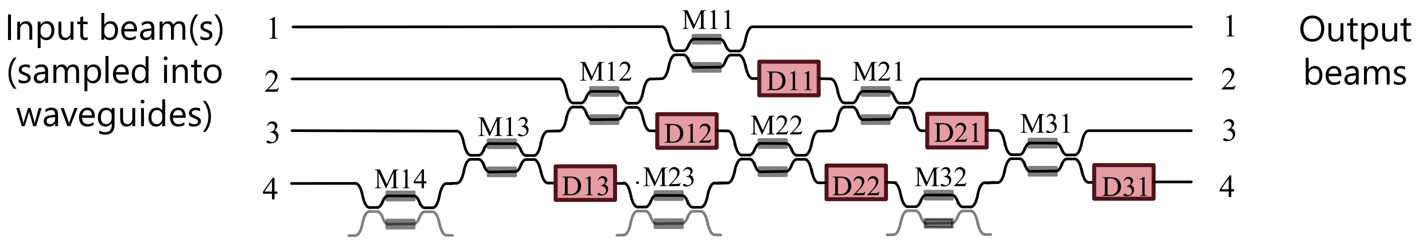
If we make these detectors mostly transparent

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 multiple orthogonal 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

Self-configuring beam separator

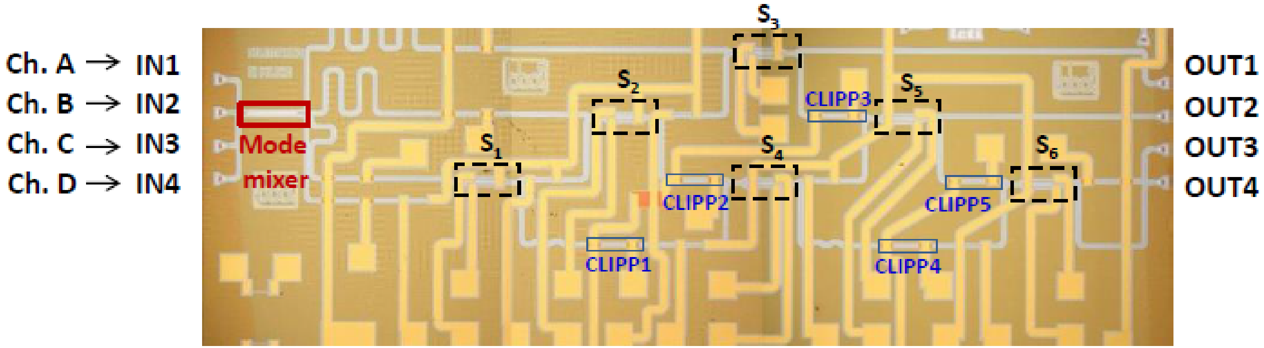
Light from four input fibers

deliberately mixed in a mode mixer

are automatically separated out again by a mesh of interferometers

by sequential power maximizations

without calculations



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

See, e.g., review W. Bogaerts et al., "Programmable photonic circuits," Nature 586, 207 (2020)

Optical and mathematical linear operations with meshes

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Universal matrix multiplier chip

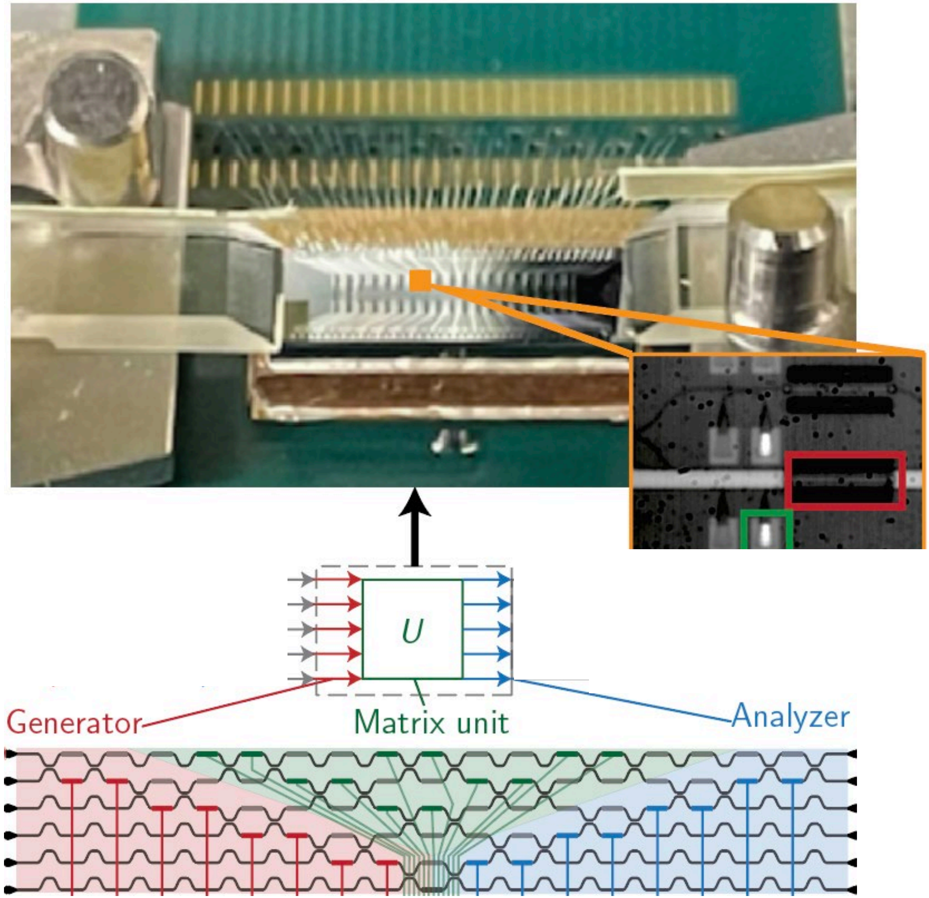
Universal matrix multiplying chip

"4x4" unitary Mach-Zehnder mesh with

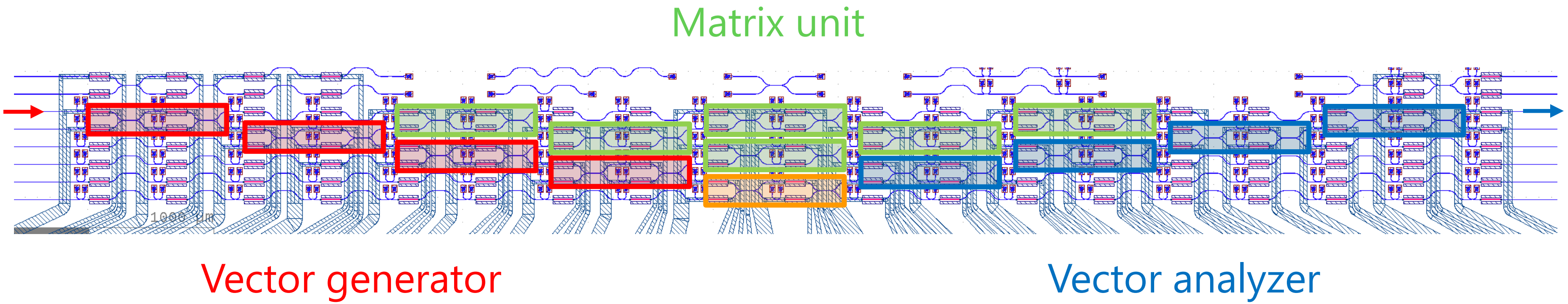
- a "generator" to create any complex input vector
- an "analyzer" to measure the complex output vector

This can be programmed to implement

any "unitary" (loss-less) transformation from the inputs to the outputs



Mask layout and block diagram



Universal matrix multiplier chip

Full complex matrix multiplication

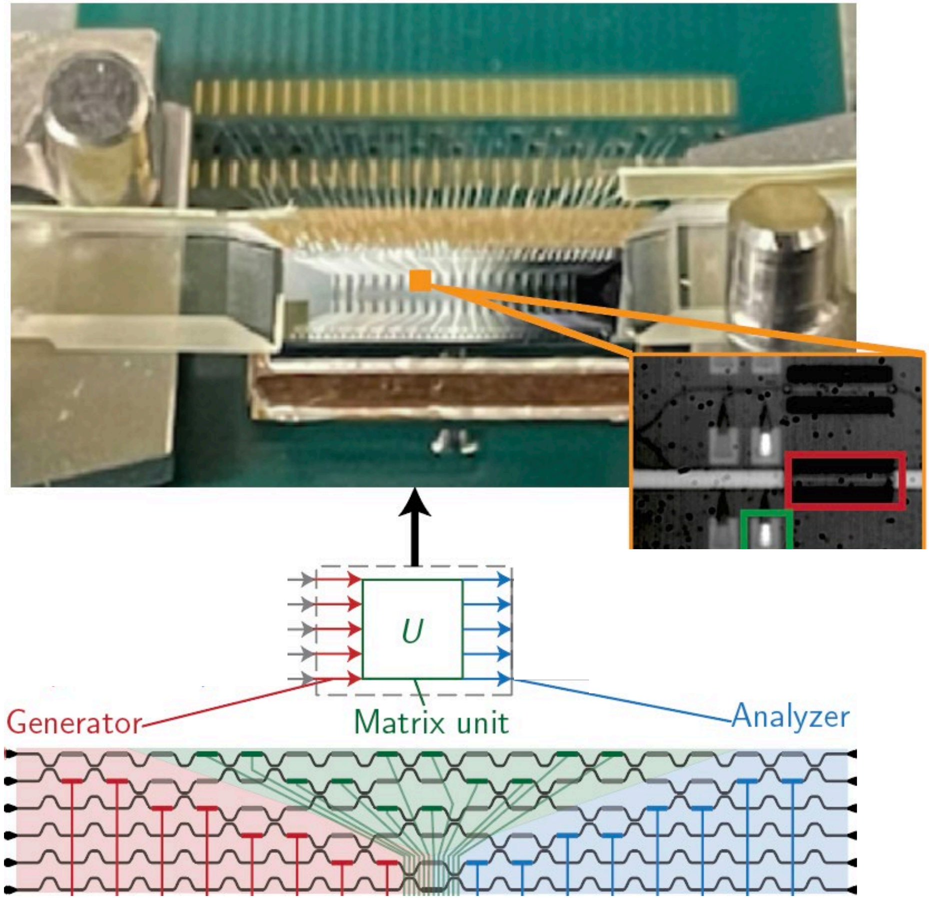
with vector generation and vector analysis

Photonic back-propagation neural net training

S. Pai, Z. Sun, T. W. Hughes, T. Park, B. Bartlett, I. A. D. Williamson, M. Minkov, M. Milanizadeh, N. Abebe, F. Morichetti, A Melloni, S. Fan, O. Solgaard, D. A. B. Miller, "Experimentally realized in situ backpropagation for deep learning in photonic neural networks," **Science** 380, 398-404 (2023)

Digital matrix multiplication for cryptography

S. Pai, T. Park, M. Ball, B. Penkovsky, M. Dubrovsky, N. Abebe, M. Milanizadeh, F. Morichetti, A. Melloni, S. Fan, O. Solgaard, and D. A. B. Miller, "Experimental evaluation of digitally verifiable photonic computing for blockchain and cryptocurrency," **Optica** 10, 552-560 (2023)



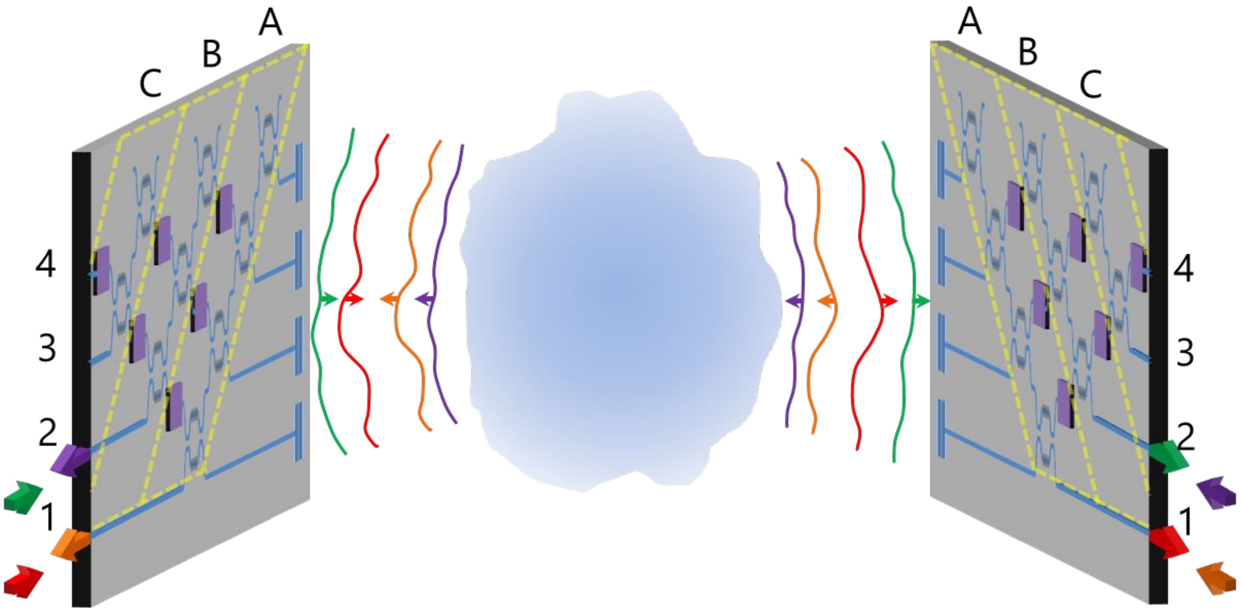
Establishing optimum orthogonal channels

In this architecture, using meshes on both sides

we proposed we could find optimal orthogonal channels through a scatterer

between waveguides on the left and waveguides on the right

by iterating back and forward between the two sides



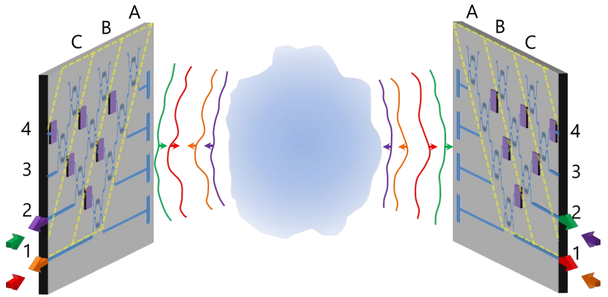
"Establishing optimal wave communication channels automatically," J. Lightwave Technol. 31, 3987 (2013)

Using optics to *perform* linear algebra

By power maximizing on rows of the mesh at both sides

- this circuit can automatically find the best orthogonal channels between the two sides
  - physically performing the singular-value decomposition of the optical system

This is a true optical computer!

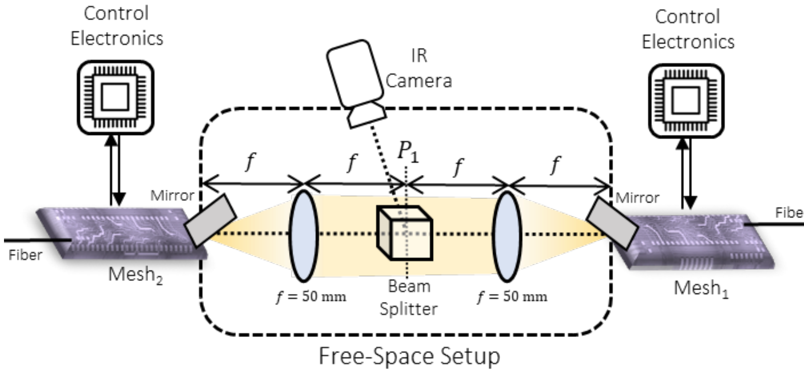


"Establishing optimal wave communication channels automatically," J. Lightwave Technol. 31, 3987 (2013)

See also

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

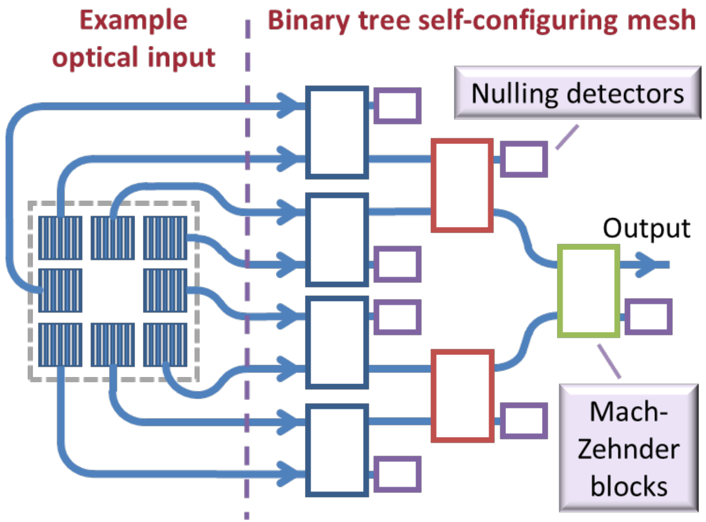
- for a general discussion of waves and modes
  - including the "communication modes" that this system finds



S. SeyedinNavadeh et al., "Determining the optimal communication channels of arbitrary optical systems using integrated photonic processors," Nat. Photon. **18**, 149-155 (2024)

Measuring and generating arbitrary beams

- Self-configuring this "binary tree" layer to route all power to the output
  - automatically measures the relative amplitudes and phases of the input light
    - with the values deduced from the resulting mesh settings.
- Run backwards, it can generate any beam emerging from the "inputs"
  - generation of arbitrary beams
  - reference-free measurement of arbitrary beams



"Analyzing and generating multimode optical fields using self-configuring networks," Optica 7, 794 (2020)

See also J. Bütow et al. "Spatially resolving amplitude and phase of light with a reconfigurable photonic integrated circuit," Optica 9, 939 (2022)

Optically separating exoplanets

Finding exoplanets around distant stars is optically very challenging

- the star may be 10^{10} times brighter than the planet
  - and the planet may lie in the weak wings of the star's diffraction pattern in the telescope

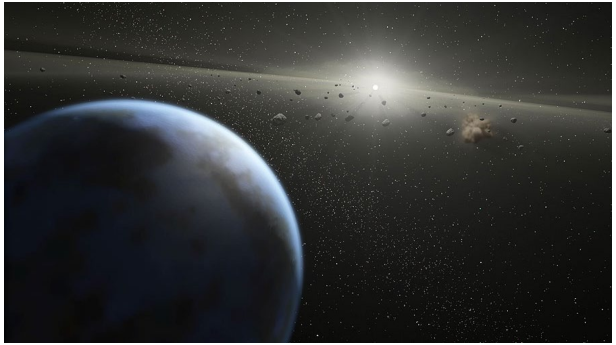
Interferometer meshes may allow

- optimized modal filtering
  - to suppress the star "modes"
    - to improve the rejection of the star light

Preliminary experiments with meshes are already showing ~ 90dB rejection

Annie Kroo – Tuesday afternoon "Photonic Integrated Circuits for Edge Computation"

Dan Sirbu et al., "AstroPIC: near-infrared photonic integrated circuit coronagraph architecture for the Habitable Worlds Observatory," Proc. SPIE 13092, 130921T (2024)



Use a programmable photonic mesh to provide optimal modal filtering to reject star light and pass possible exoplanet light

Separating partially coherent light

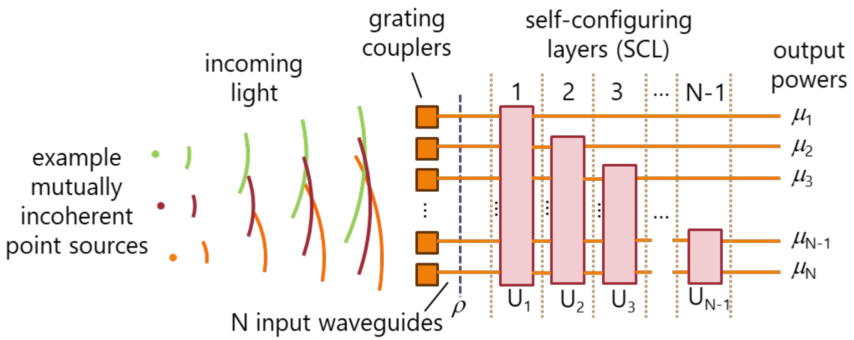
With partially coherent input light

- by power maximizing on the successive self-configuring layers
  - this circuit can measure the coherency matrix of that light
    - simultaneously separating it into its
      - mutually incoherent and mutually orthogonal components

No other known apparatus can apparently perform this separation

This concept can also be extended to

- measure the single photon density matrix
- automatically perform a modal analysis of entanglement with two-mesh bipartite self-configuring optics



Roques-Carmes et al., "Measuring, processing, and generating partially coherent light ..." LSA **13**, 260 (2024)

C. Roques-Carmes, A. Karnieli, D. A. B. Miller, and S. Fan, "Automated Modal Analysis of Entanglement with Bipartite Self-Configuring Optics," ACS Photonics (2025) https://doi.org/10.1021/acsphotonics.5c00813

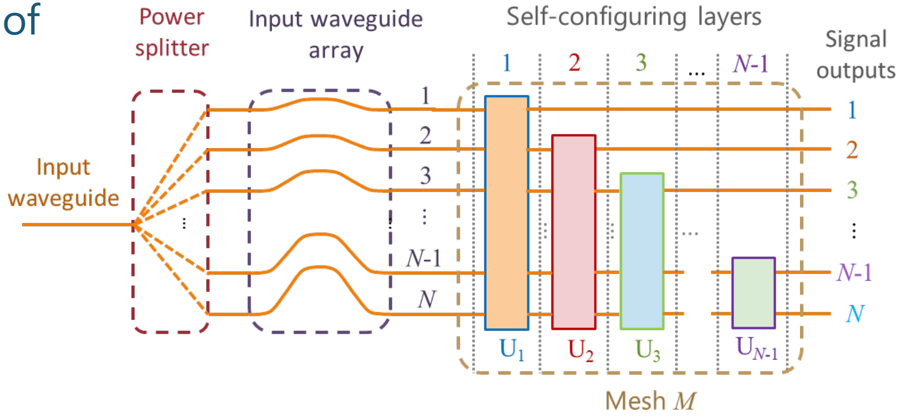
Shanhui Fan – Wednesday afternoon "Process quantum states with waveguide meshes"

Programmable and self-configuring filters

This proposed circuit can function like an arrayed waveguide grating filter
- but has a spectral response that is fully programmable
  - so it can implement any linear combination of such filter functions
  - and allows multiple different simultaneous filter functions

It can also
- self-configure to specific wavelengths
- reject N-1 arbitrary wavelengths
- measure and separate temporally partially coherent light
  - the Karhunen-Loève decomposition

D. A. B. Miller, C. Roques-Carmes, C. G. Valdez, A. R. Kroo, M. Vlk, Shanhui Fan, and O. Solgaard, "Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)



C. G. Valdez, A. R. Kroo, M. Vlk, C. Roques-Carmes, Shanhui Fan, D. A. B. Miller, and O. Solgaard, "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," http://arxiv.org/abs/2509.12059

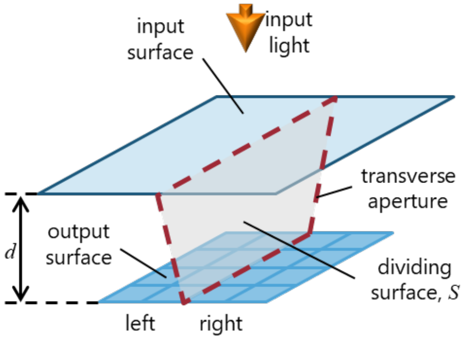
Some other recent basic optics

Why optics needs thickness

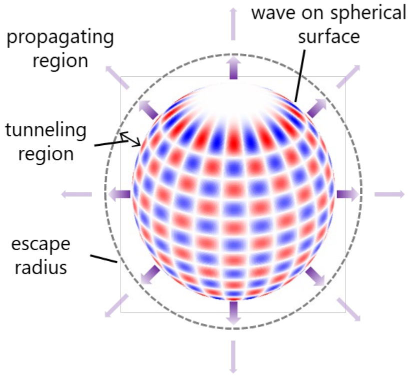
- We can't make optics infinitely thin
  - or why your cell phone has a bump for the lens
- because information has to flow from left to right inside it
  - through a "transverse aperture"
    - e.g., as in an imager
      - and the aperture has to be large enough support the necessary channels

Why it's so hard to beat the diffraction limit

- Complicated waves must tunnel to get in or out of small volumes



"Why optics needs thickness," Science 379, 41 (2023)



D. A. B. Miller, Z. Kuang, O. D. Miller, "Tunneling escape of waves," Nat. Photon. **19**, 284–290 (2025)

Conclusions

Interferometer meshes allow many different and fully programmable optical and mathematical functions

- with self-configuration to adapt to the problem of interest
- and to stabilize complex interferometric circuits

Applications include

- mathematical operations
- reference-free measurement of arbitrary optical fields
- generation of arbitrary beams
- automatically finding best channels
- modal filtering to separate and suppress arbitrary beams
- separation and measurement of partially coherent light
- extensions to similar concepts in the frequency domain

Other recent related theoretical work

- Why optics needs thickness
- Why beating diffraction is so hard – tunneling escape of waves

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