Photons à la mode

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Photons à la mode?

Photons à la mode

served with ice cream?

No!

in the most modern style or fashion?

Sort of …

a pun on the word “mode”

Yes!

Why?

because a photon must be in a mode

and our new understanding of modes tells us new things we can do with photons

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Summary

Important things we do with photons

The most important aspects of photons we are not yet exploiting but really need to

How do we get to photons?

We start with modes

What has changed with modes?

- our understanding of how many modes we actually have
- what those modes really are
- how to manipulate them

Mach-Zehnder interferometer meshes

including with partially coherent light

A new basic theorem in optics

How to bounce photons off empty space

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Important things we do with photons

For example

- solar energy
- imaging detectors
  - essentially all are quantum detectors
- sensing
  - including microscopy, spectral sensing, remote sensing, …
- "classical" optical communications
  - e.g., optical fiber
- communicating quantum states
  - including entangled states
- quantum computation
  - e.g., based on the "boson beamsplitter" (Hong-Ou-Mandel)
- …

But there is one more that we really need to do now …

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A new generation of optical interconnects?

Most energy in information processing is in interconnects, in

- running interconnect circuits, especially for

  time-multiplexed links - pJ/bit energies

  Avoid time-multiplexing by using the parallelism of free-space optics

  run "wide and slow" e.g., 1000's or 10,000s of channels

- charging wires

  Photonics can avoid charging wires

  especially with well integrated optoelectronics

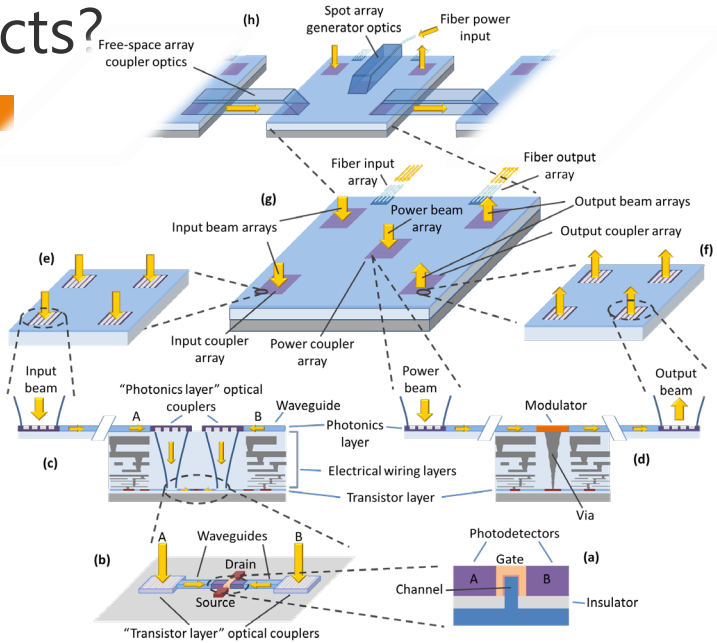
  fundamentally eliminating energy by "quantum impedance conversion"

A next generation of highly parallel free-space optical interconnects could exploit both of these

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



"Straw man" system concept

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

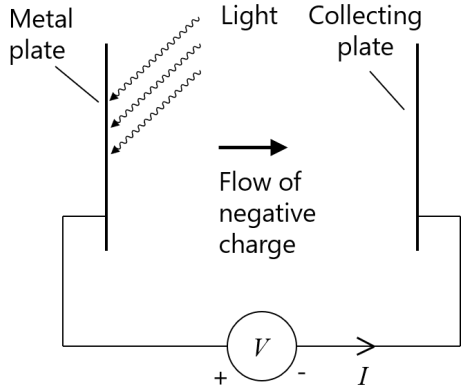
See also this video (OFC 21, dabm.stanford.edu/videos/#OFC2021)

Quantum impedance conversion

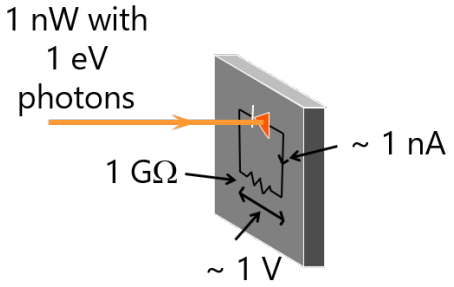
A key quantum advantage that can reduce energy

The photoelectric effect means

- we can 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”
- Avoids charging wire capacitance (pf/cm) to the signal voltage (which needs ~ pJ/bit energies)
- Needs
  - good low-capacitance (e.g., 1fF) integration of optoelectronic devices
  - low energy (<<10 fJ) optical output devices

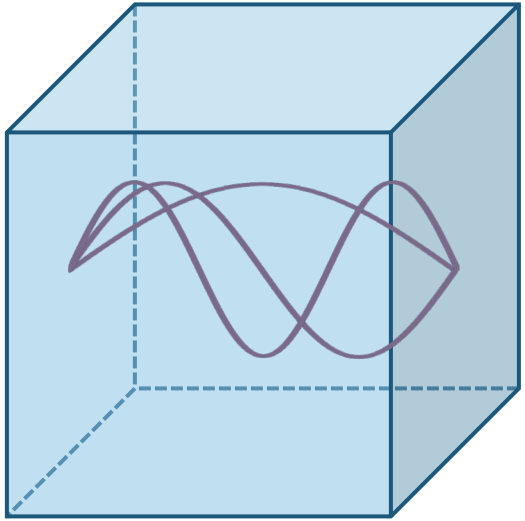


Photoelectric effect (Hertz, 1887)



“Optics for low-energy communication inside digital processors: quantum detectors, sources, and modulators as efficient impedance converters,” Optics Lett. **14**, 146

How we get to photons



We start with modes

We write the classical electromagnetic field as a combination of “modes”

usually resonator modes

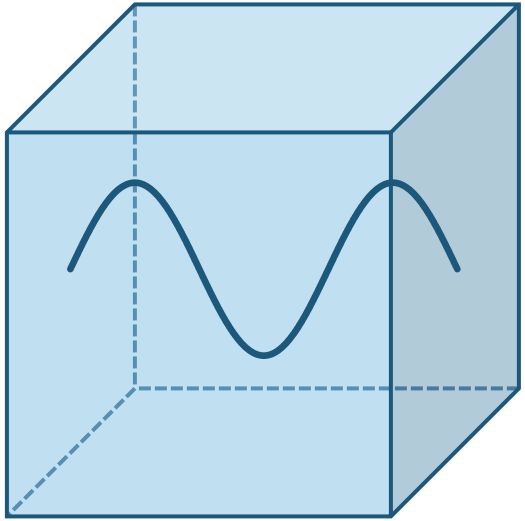
each of which is spatially and/or polarization orthogonal to all other modes

in an energy sense

so that the energy of a (classical) linear combination of these modes

is the sum of the energies in each mode

How we get to photons



Then write each mode in a form compatible with Hamilton's equations with

- effective position "q" (which can be the electric field mode amplitude) and
- effective momentum "p" (which can be the magnetic field mode amplitude)

Then introduce the usual "transition to quantum" trick of substituting

$$\hat{p} = -i\hbar \frac{d}{dq}$$

which gets us to an equation for a quantum harmonic oscillator for each mode

How we get to photons

The quantum harmonic oscillator for each mode

then has quantized energy levels

separated by $\hbar\omega$

Then we make a purely semantic shift

Instead of saying that the mode is in its qth level of excitation

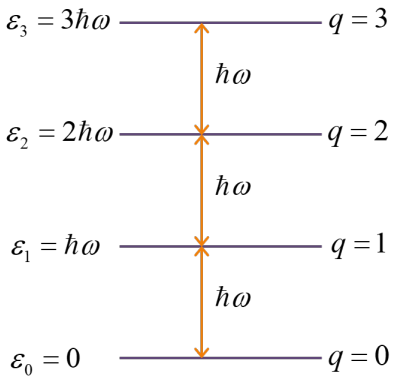
we say it contains q photons

Note: we do not have to introduce photons

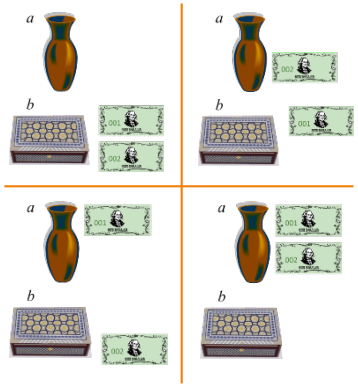
we could continue just to talk about energy levels of the mode

which actually makes the counting easier

no need to introduce "identical particles"



Field modes as oscillators
Electromagnetic mode Hamiltonian
Lecture slides



Bank account analogy for counting states
Lecture slides

Particles or waves?

The wave aspects are characteristics of the mode

e.g., interference, diffraction and propagation

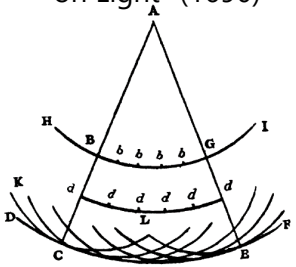
The particle aspects are characteristics of the occupation levels of the mode

e.g., detecting and counting photons

Viewed this way

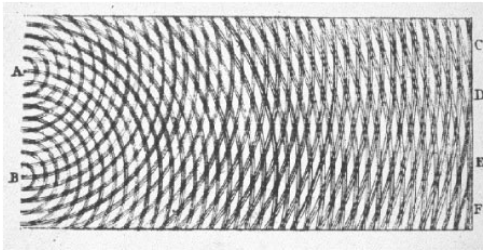
there is little problem about wave-particle duality

Huygens' "Treatise on Light" (1690)

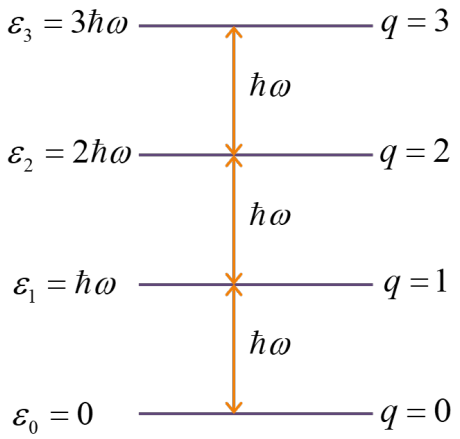


See also "Huygens's wave propagation principle corrected," Optics Lett. **16**, 1370 (1991)

Young's drawing of the two-slit experiment



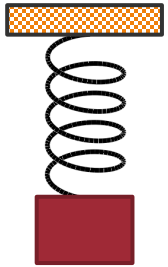
T. Young, "Course of Lectures on Natural Philosophy and the Mechanical Arts," 1807



What are modes?

We can give a definition of a mode

A mode is an eigenfunction of an eigen problem describing a physical system





Modes have useful mathematical properties, e.g.,

orthogonality

completeness

But what modes should we use in optics?

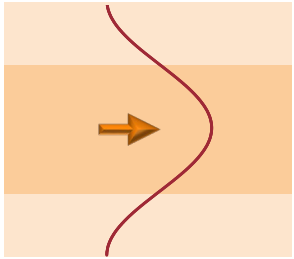
e.g., if we have no resonator

or

if we are interested in counting communication channels

We also want modes that are energy-orthogonal

so they can contain photons



DM, *Quantum mechanics for scientists and engineers* (Cambridge, 2008)

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

A different way of thinking about modes and waves

When we look generally at

communications with waves

or scatterers, optical devices, or nanostructures

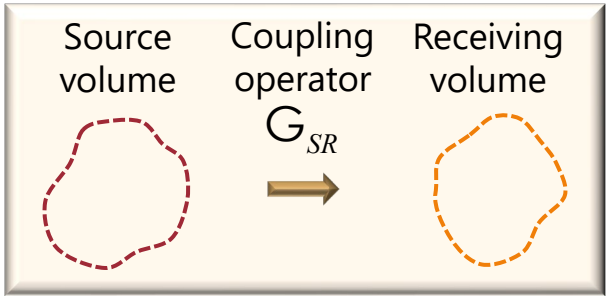
we can think in terms of

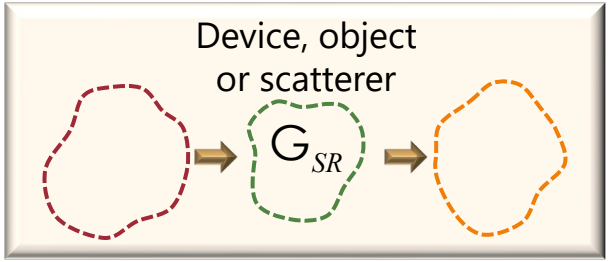
- a "source" or input space
- and a "receiving" or output space

We can ask first

what is the best choice of source function that

leads to the strongest wave in the receiving space





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

A different way of thinking about modes and waves

We see immediately a difference compared to previous “beams”

Our answer will involve **two** functions

one in the source space

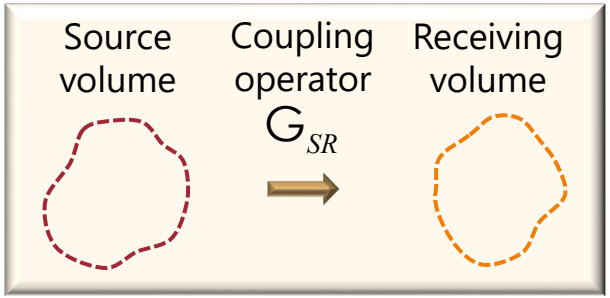
and one in the receiving space

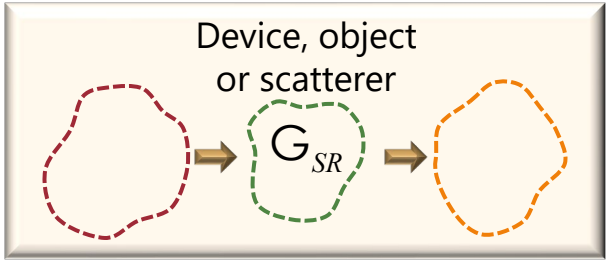
These are “modes” in **two** spaces

not one space

The answer is **not** the “beam” between the spaces

though we can calculate that afterwards





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

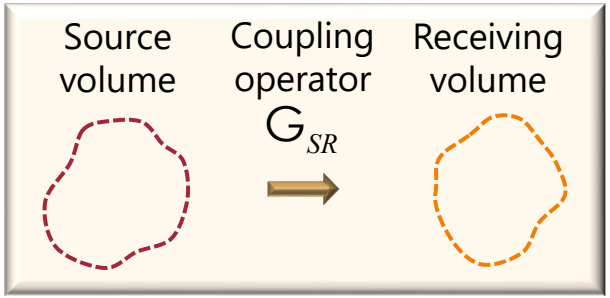
A different way of thinking about modes and waves

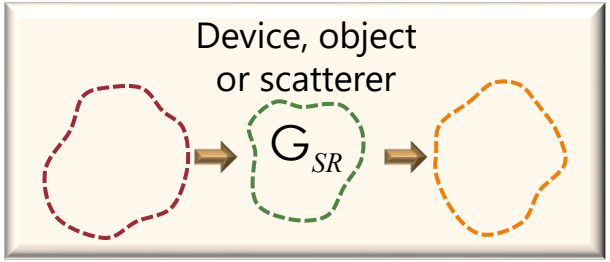
The best and orthogonal mode pairs
each called a "communication mode"
- one function in the source space
- one (wave) function in the receiving space

exist for any source and receiving space
and any coupling operator

They can formally be found from
singular value decomposition (SVD) of the coupling operator
which is easily performed on the computer
and also gives coupling strengths
"singular values"

These "receiving" modes are also suitable for holding photons
with no non-existent resonator required





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

Communication modes

Communication modes allow

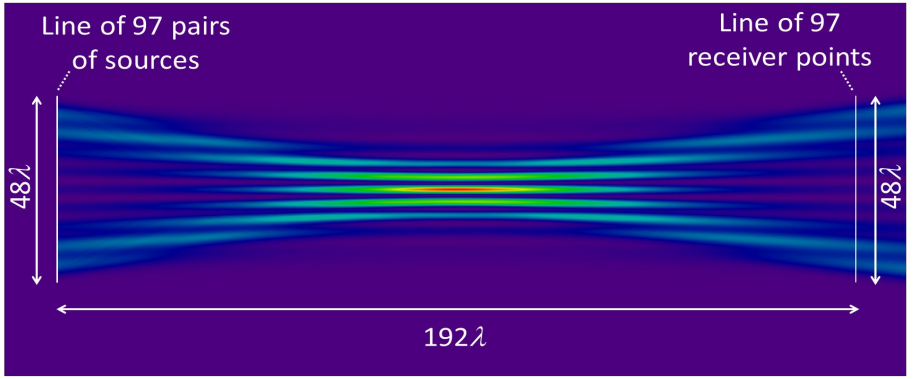
- A rigorous "communications mode" counting of communications channels

including the conclusion that there is always a finite number of usable channels

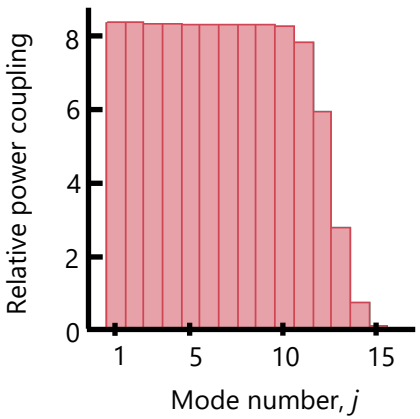
including specific new limits for various optical systems

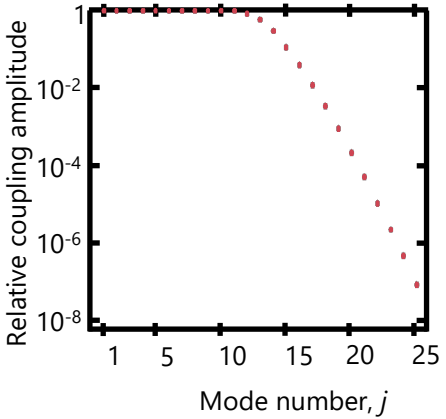
"Waves, modes, communications and optics," Adv. Opt. Photon. 11, 679-825 (2019)

"Tunneling escape of waves," Nat. Photon. **19**, 284–290 (2025)



Example beam for strongest communication mode





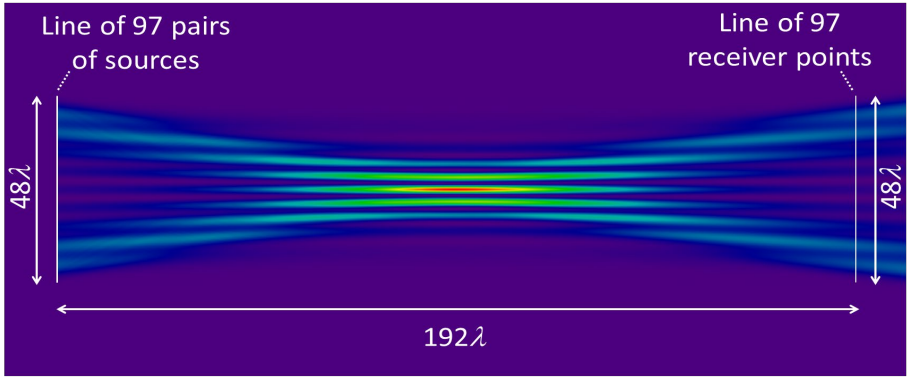
Example communication mode coupling strengths

Communication mode coupling strengths
- are generally similar or fall off slowly with increasing mode number
  - up to a characteristic number
    - a "paraxial heuristic number" for paraxial optical situations
      - which agrees with diffraction heuristics
- then falling off rapidly and quasi-exponentially

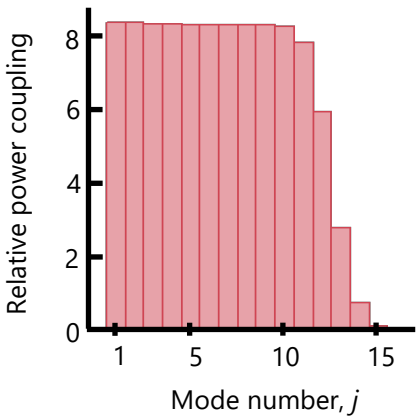
Empirically true for a very wide range of source and receiving spaces

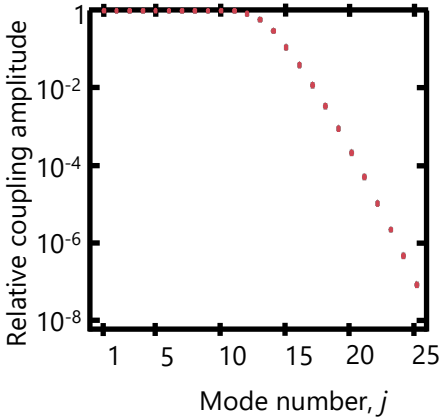
"Waves, modes, communications and optics," Adv. Opt. Photon. 11, 679-825 (2019)

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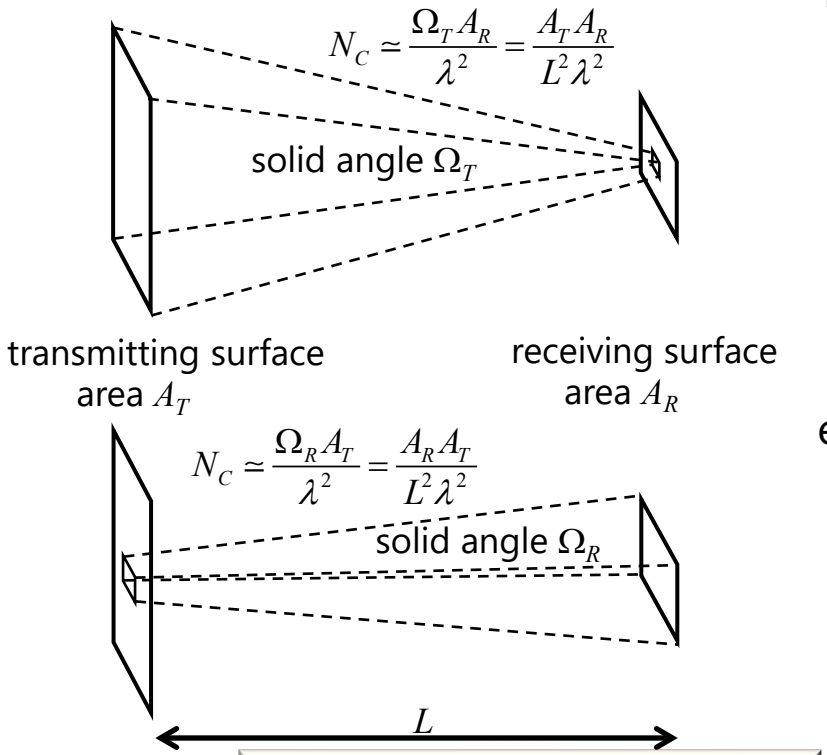


Example beam for strongest communication mode





Number of channels in paraxial optics



JLT **35**, 343 (2017)

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

The practical number of optical channels (communication modes) (per polarization)

between two surfaces of areas A_T and A_R

separated by a distance L

at a wavelength λ

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

paraxial heuristic number

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

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

shows the large number of channels possible in free-space interconnects

Generating a volume field

Communication modes allow

- Calculation of the optimum source to give any specific wave in any volume

For example, we can choose dense sets of points in

a planar rectangular optical source "volume"

which might be a spatial light modulator or a metasurface

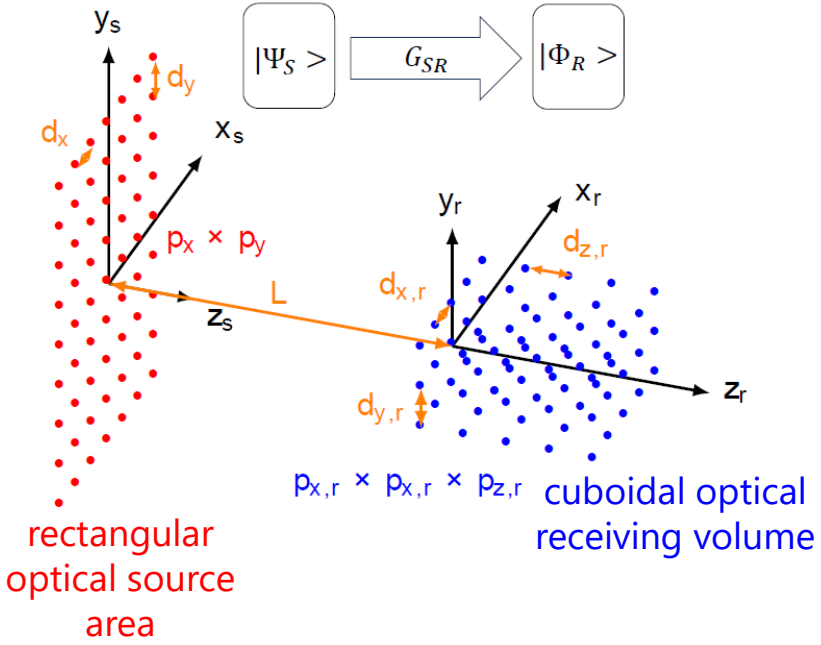
a cuboidal optical receiving volume

where we want to construct a field

and we can use communication modes

to design sources for desired volume fields

and tell us what fields we cannot generate



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

de Angelis et al., "Structuring light waves in 3D volumes with high precision using communication mode optics," Optica **12**, 1502-1513; "Multi-plane spatially resolved phase structuring using optical communication modes," J. Opt. **28**, 065603 (2026)

Communication modes for fundamental physics

Communication modes allow

- 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

"All linear optical devices are mode converters," Opt. Express **20**, 23985-23993 (2012)

DM, L. Zhu, and S. Fan, "Universal modal radiation laws for all thermal emitters," PNAS **114**, 4336 (2017)

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

Why optics needs thickness

Communication modes allow

- An understanding of why optics needs thickness, and how much it needs

Think of an optical system with

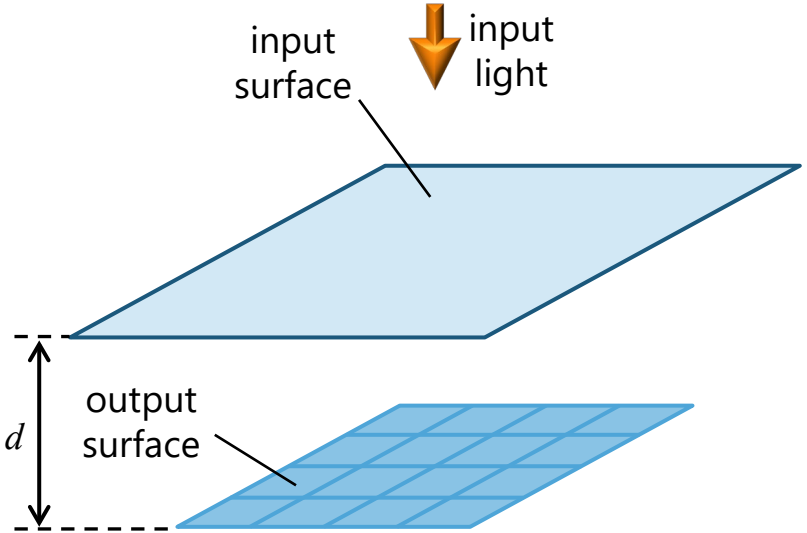
an input surface

such as a lens surface or metasurface

an output surface

such as an image sensor plane

with a distance *d* between them



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

The key idea – channels through a transverse aperture

Now imagine we divide each surface in two parts

left and right

by passing an imaginary mathematical dividing surface *S* through them

This defines a "**transverse aperture**"

Because of what we want the system to do

some number *C* of channels must pass

from right to left (or left to right)

through this aperture

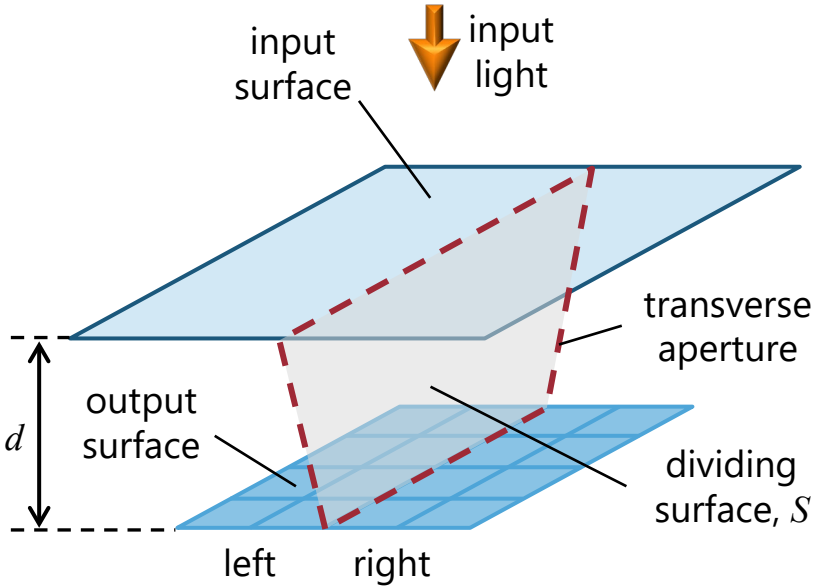
can be established through SVD

communication modes

C is the "**overlapping nonlocality**" of the system

This transverse aperture must be large enough to allow that number of channels to propagate through it

hence thickness



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

Tunneling escape of waves

Communication modes allow

- A general form of diffraction theory, valid for all sizes and shapes of objects

  and the real reason why we can only get so many orthogonal waves in or out of any volume

  tunneling escape of waves

Question:

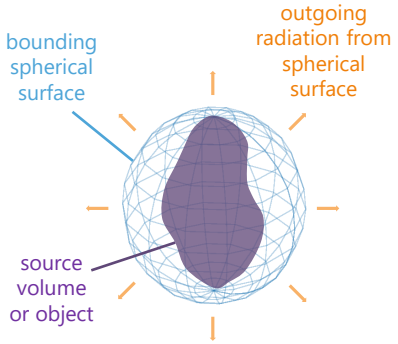
Why is there always a rapid, quasi-exponential fall-off in communication mode coupling strengths

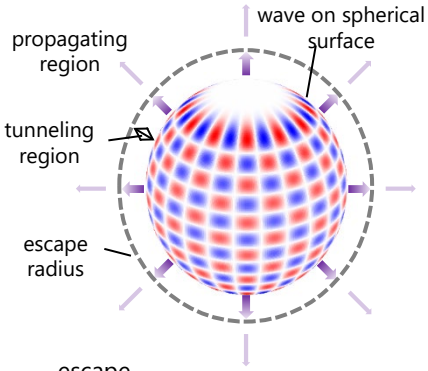
past some number of modes?

Answer:

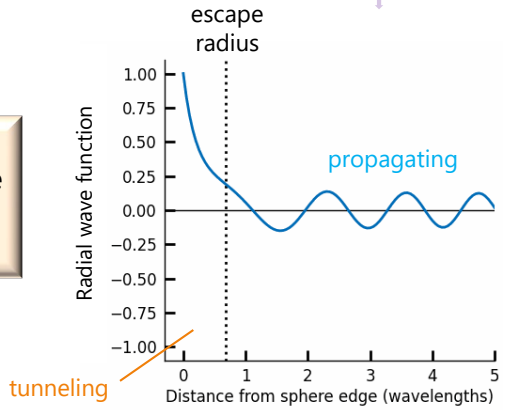
Because, if we try to have too "complicated" a wave escape some volume

components of it must tunnel radially to escape





Waves on the spherical bounding surface that are too complicated must tunnel to escape



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

Tunneling escape of waves

By considering a bounding spherical volume surrounding the sources

using spherical waves as the basis

we see explicitly the onset of radial tunneling

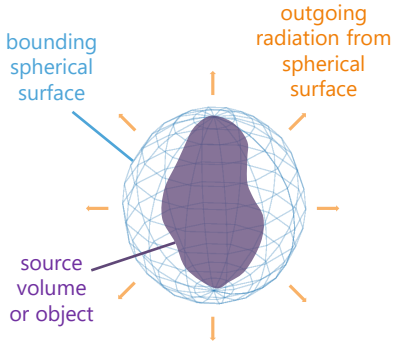
giving a simple answer for the number of modes that can "escape" without tunneling

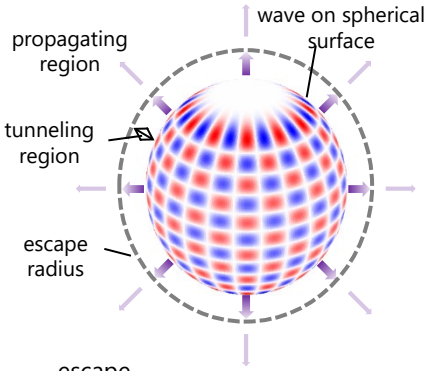
The quasi-exponential fall-off

is understood as a consequence of tunneling

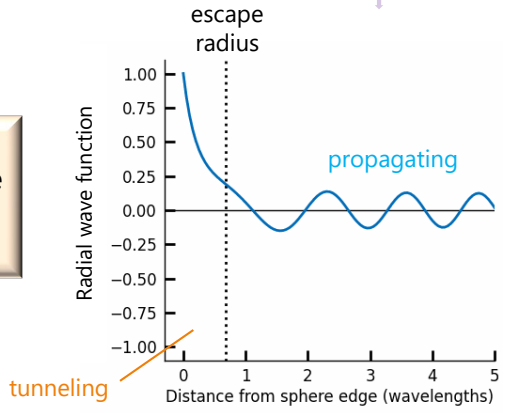
This is the real origin of diffraction limits

Tunneling escape of waves





Waves on the spherical bounding surface that are too complicated must tunnel to escape



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

Manipulating modes with Mach-Zehnder arrays - Self-aligning beam coupler

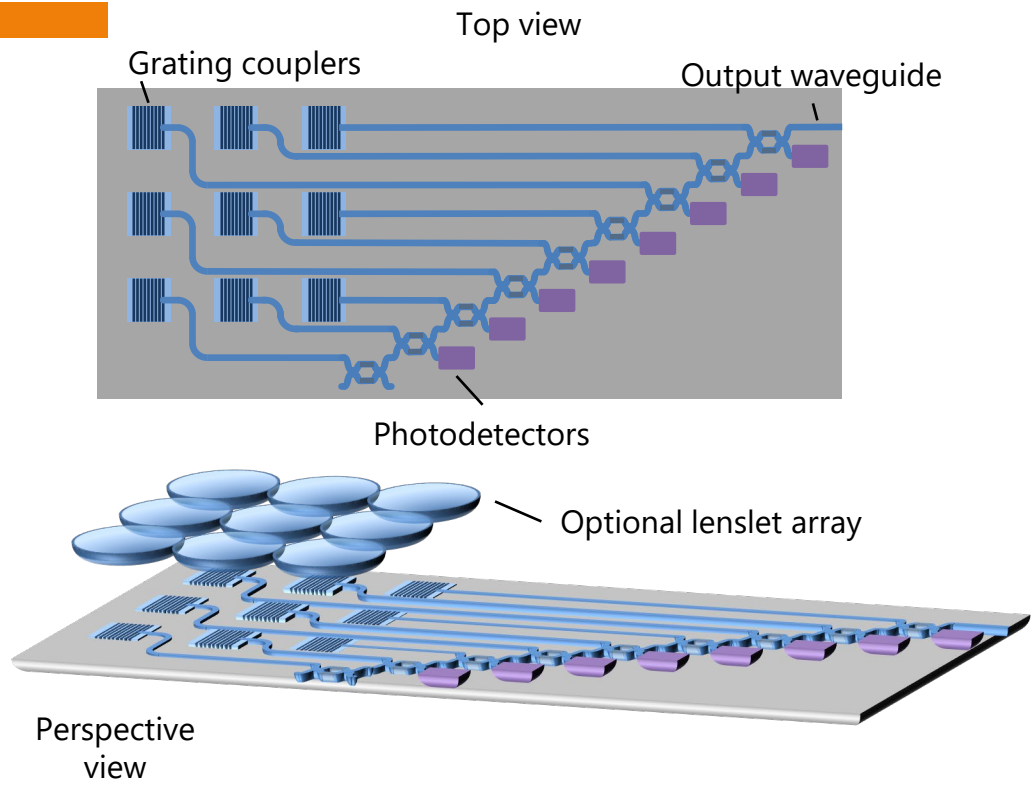
By progressively nulling out the power on each photodetector

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)

Mach-Zehnder interferometer meshes

Mach-Zehnder interferometer meshes in silicon photonics

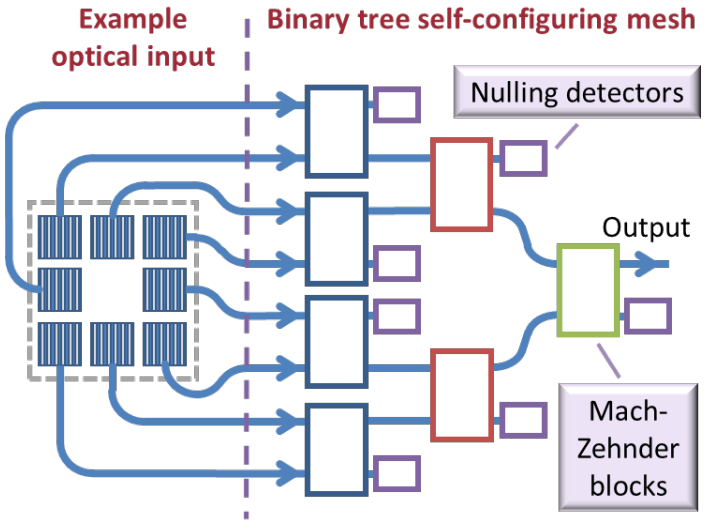
"universal" linear optical components

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

enable us to manipulate complex optical modes

Many potential applications

- self-aligning beam couplers
- **measuring amplitude and phase of optical fields**



"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)

Review: W. Bogaerts et al., "Programmable photonic circuits," Nature **586**, 207–216 (2020)

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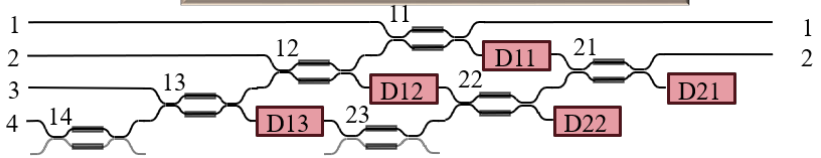
- self-aligning beam couplers
- measuring amplitude and phase of optical fields
- **separating overlapping orthogonal beams**

Review: W. Bogaerts et al., "Programmable photonic circuits," Nature **586**, 207–216 (2020)

Input beam(s) (sampled into waveguides)

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

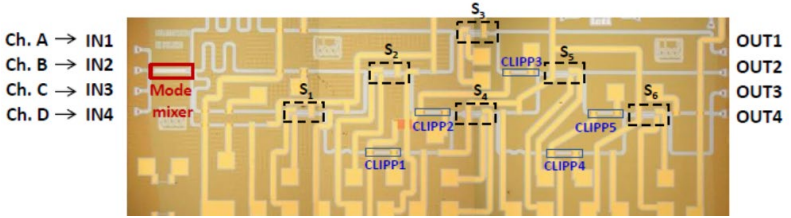
Output beams



self-configure the first "diagonal line" to route a first beam to output 1

an orthogonal beam will pass into the second diagonal line

which can be self-configured to route the second beam to output 2



extend to separate multiple beams

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

A. Ribeiro et al. "Demonstration of a 4 × 4-port universal linear circuit," Optica **3**, 1348 (2016)

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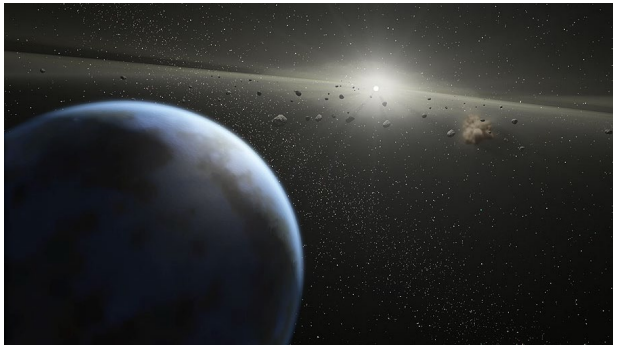
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- **modal spatial filtering – e.g., for exoplanets round stars**



Dan Sirbu et al., "AstroPIC: near-infrared photonic integrated circuit coronagraph architecture for the Habitable Worlds Observatory," Proc. SPIE 13092, 130921T (2024); "AstroPIC III: advancing the near-infrared photonic integrated coronagraph for the Habitable Worlds Observatory," in Space Telescopes and Instrumentation 2026: Optical, Infrared, and Millimeter Wave (SPIE, 2026), Vol. 14145, p. 2199.

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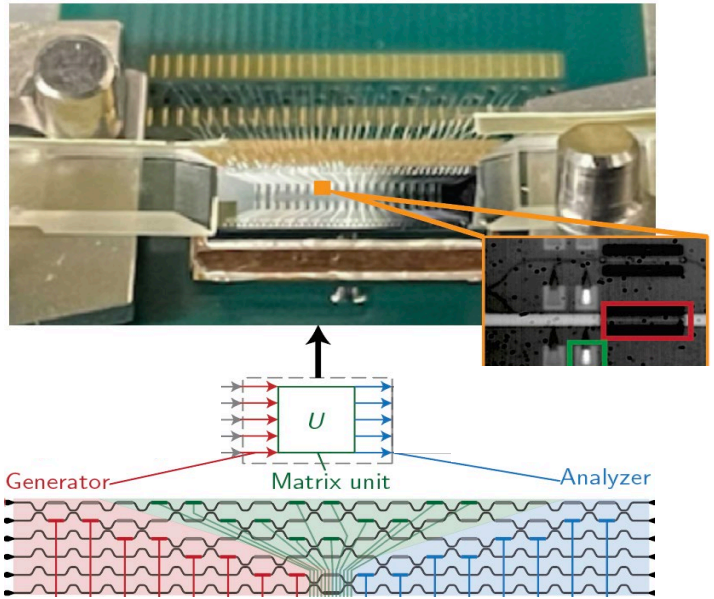
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- **matrix multiplication and inversion**



S. Pai et al., "Experimentally realized in situ backpropagation for deep learning in photonic neural networks," **Science** 380, 398-404 (2023)

S. Pai et al., "Experimental evaluation of digitally verifiable photonic computing for blockchain and cryptocurrency," **Optica** 10, 552-560 (2023)

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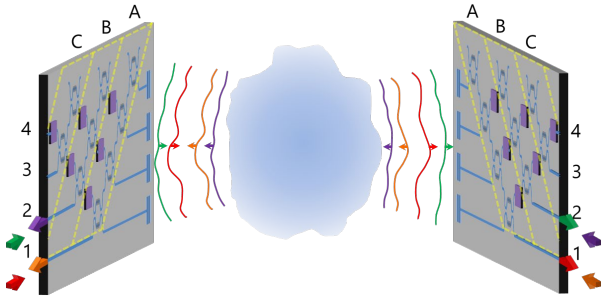
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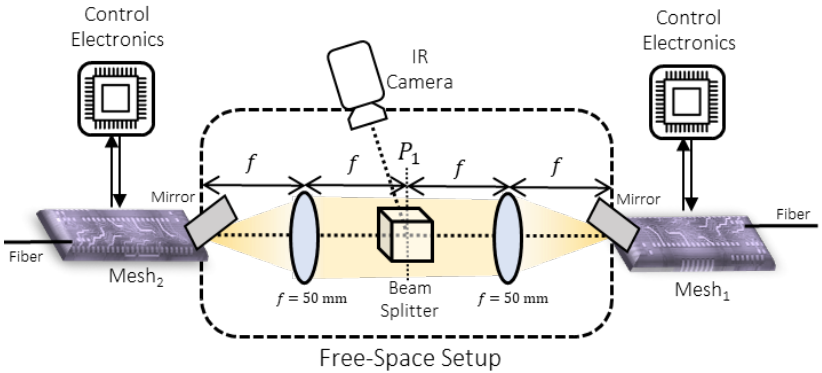
Many potential applications

- self-aligning beam couplers
- measuring amplitude and phase of optical fields
- separating overlapping orthogonal beams
- modal spatial filtering – e.g., for exoplanets round stars
- matrix multiplication and inversion
- **finding the best channels through an optical system**

Review: W. Bogaerts et al., "Programmable photonic circuits," Nature **586**, 207–216 (2020)



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



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

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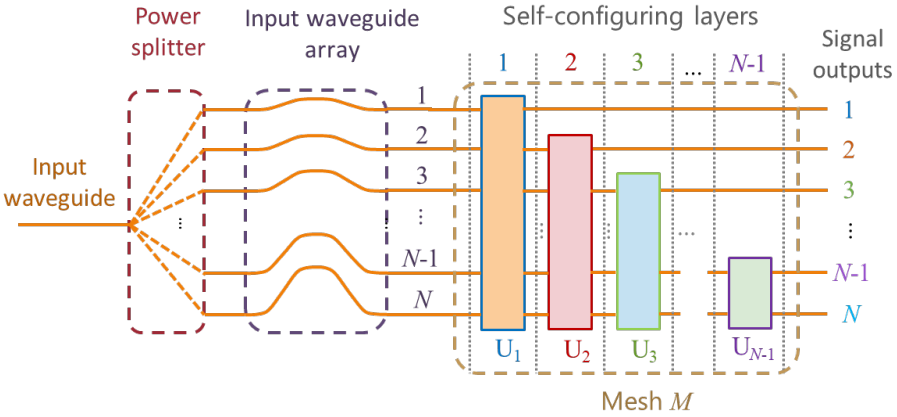
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- finding the best channels through an optical system
- **programmable spectral filters**



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 et al., "Programmable optical filters based on feed-forward photonic meshes," Light Sci Appl **15**, 350 (2026)

Review: W. Bogaerts et al., "Programmable photonic circuits," Nature **586**, 207–216 (2020)

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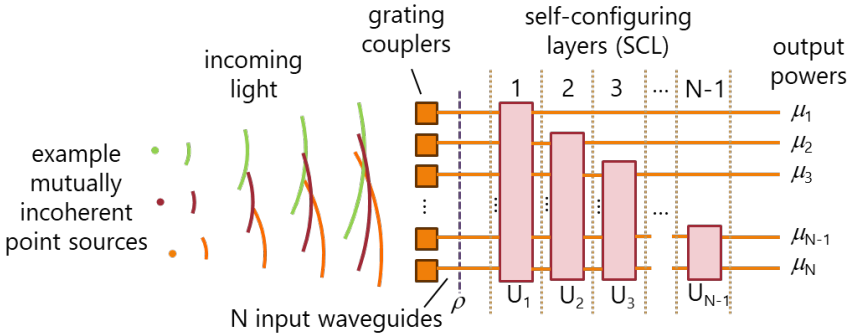
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- modal spatial filtering – e.g., for exoplanets round stars
- matrix multiplication and inversion
- finding the best channels through an optical system
- programmable spectral filters
- **analyzing partially coherent light**

…

Review: W. Bogaerts et al., "Programmable photonic circuits," Nature **586**, 207–216 (2020)



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

Mor at al., "Automatic on-chip separation of partially coherent light into its mutually incoherent components," Nature Photonics doi: 10.1038/s41566-026-02035-6

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

Working with partial coherence

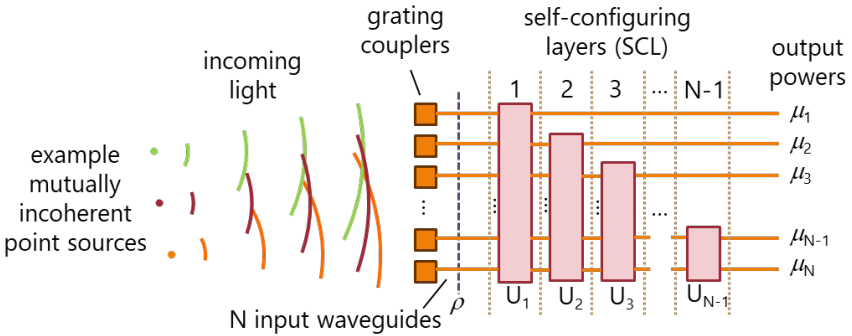
Partially coherent light can always formally be described as a set of "**coherence modes**"

a set of mutually completely incoherent and mutually orthogonal components

Note these modes are describing the light field

not the optical apparatus itself

unlike resonator modes or communication modes



Mor at al., "Automatic on-chip separation of partially coherent light into its mutually incoherent components," Nature Photonics doi: 10.1038/s41566-026-02035-6

Working with partial coherence

This "coherence mode" decomposition has been known mathematically for some time (E. Wolf, J. Opt. Soc. Am. **72**, 343 (1982))

but only as an analytic tool

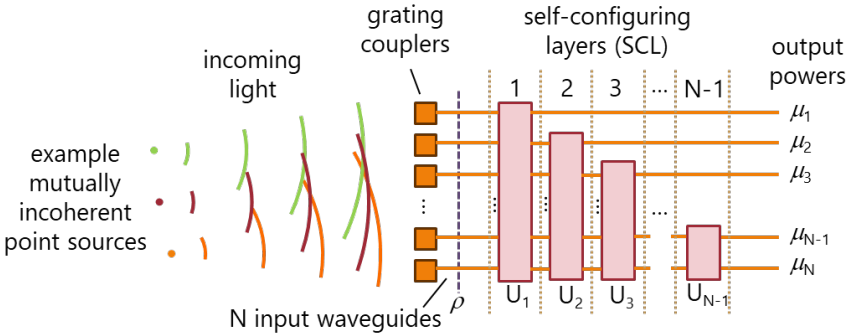
These modes are the eigenfunctions of the "coherency matrix"

which is equivalent to the single-photon density matrix

with the mode powers being the eigenvalues

Now we can physically separate partially coherent light into these coherence modes

Just requires successive power maximizations from successive self-configuring layers



Mor at al., "Automatic on-chip separation of partially coherent light into its mutually incoherent components," Nature Photonics doi: 10.1038/s41566-026-02035-6

Maximum brightness theorem for waves

New theorem in optics

> In passing through a passive optical system, the power in the *i*th most powerful mutually incoherent mutually orthogonal component of the field cannot increase

Supersedes previous brightness theorems

e.g, constant brightness (or radiance) theorem

and gives answers, (coherence) mode by (coherence) mode

Equivalently, if we write the eigenvalues of the input coherency matrix in descending (non-increasing) order

$$\mu_{S1} \geq \mu_{S2} \geq \cdots \geq \mu_{Sn}$$

and similarly for the output coherency matrix

$$\mu_{R1} \geq \mu_{R2} \geq \cdots \geq \mu_{Rn}$$

then $\mu_{Ri} \leq \mu_{Si}$

"Maximum brightness theorem for waves," https://arxiv.org/abs/2608.12578.

How to bounce photons off empty space

If we have the photons in spherical waves

then those spherically converging waves will bounce off free space

with larger “cloaked volumes” for more complex waves

Since spherical waves are a complete set

then we can see that trying to focus below the “diffraction limit”

will involve spherical waves that are too complicated to get into the desired focal volume

They simply bounce off



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

Conclusions

Obviously, photons have already proved themselves to be very useful

but we are only just getting started

A key point of this talk is that the modes that contain the photons

- are now understood much better
- can now be controllably manipulated

both classically and quantum mechanically

with arbitrary flexibility

opening new practical and fundamental opportunities for photons

with many new directions

stanford.io/3VWcMp2