# Separating light in time and space - fully resolving partial coherence

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# Fully resolving partial coherence

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C. Roques-Carmes, S. Fan
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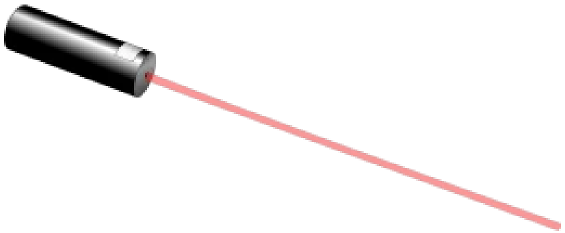
# Working with partial coherence

When we think about advanced optics

- such as metasurfaces and silicon photonics
  - at least for analysis
    - we mostly presume light is coherent
      - e.g., from a single-frequency laser

This makes analysis simpler

- and can have many applications



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# Working with partial coherence

But much light is incoherent or partially coherent

Nearly all natural light is (e.g., sunlight)

So understanding if we can use our advanced optics, e.g.,

- metasurfaces or metamaterials
- interferometer meshes

also with

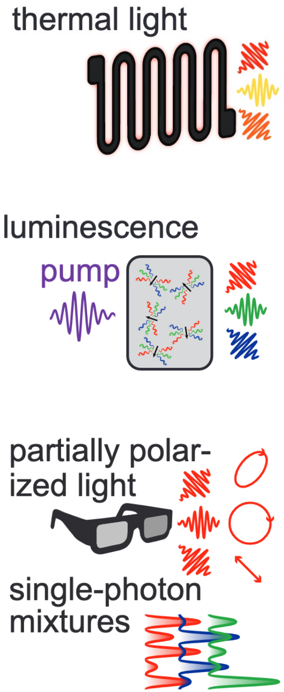
incoherent or partially coherent light

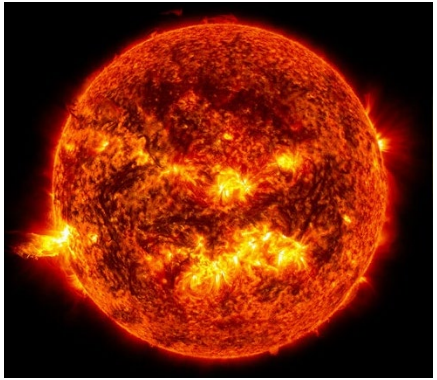
could open new possibilities

e.g., in sensing

allowing us to extract all the information that is there

even when only measuring powers



# Working with partial coherence

What information are we throwing away

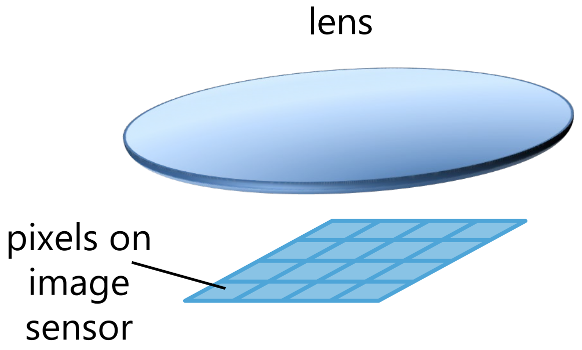
- for example, with a conventional camera?

Answer

- all the mutual coherence or "interference information" between the light landing on the different pixels

If we could collect all that information

- we would have a much more complete version of the light field
  - for example, including all "focus" and depth information
    - and even without a lens



# Working with partial coherence

In general, the light from somewhat distant, mutually incoherent sources

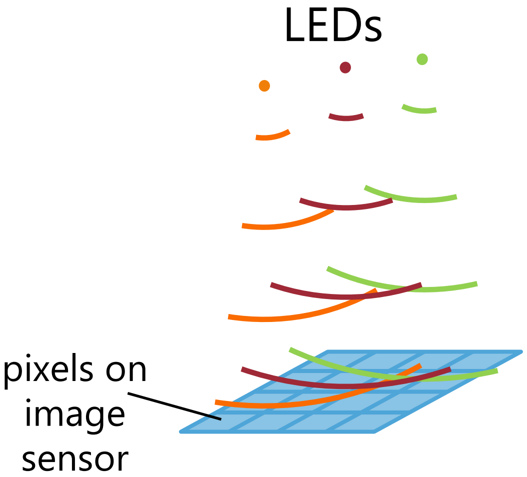
- e.g., a set of different LEDs
  - is partially coherent when we observe it

Each "point source" LED produces approximately spherical waves at our receiving surface

- which each have coherence within them

Even with all the LEDs on at once

- there still is some coherence in the arriving light
  - We could still see some interference between the light in different "pixels"




Note: we are presuming that all light is at a similar wavelength

- with coherence lengths longer than any path-length differences in our optics
  - and for this discussion we limit ourselves primarily to spatial coherence
    - Different colors here are for graphic clarity only

# Describing partial coherence – the coherency matrix

If we presume a set of possible source fields

written as mathematical vectors $|\mathbf{x}_j\rangle$

e.g., corresponding to the fields at a dense set of points

not necessarily orthogonal to one another

and which occur with probabilities $P_j$

then by definition we can write the coherency matrix as

$$\rho = \sum_j P_j |\mathbf{x}_j\rangle\langle\mathbf{x}_j|$$

This essentially contains all the information we can know

about this partially coherent field

based only on average power measurements

Note this has the same structure as

the density matrix for the light from a set of single-photon emitters

e.g., LEDs

see, e.g., J. W. Goodman *Statistical Optics (2nd edition)* (Wiley 2015)

# Diagonalizing the coherency matrix

This coherency matrix, like the density matrix, has "good" properties

it can be diagonalized on its (orthogonal) set of eigenfunctions $|\eta_m\rangle$

with real, positive eigenvalues $\mu_m$

$$\rho = \sum_m \mu_m |\eta_m\rangle\langle\eta_m|$$

So, any partially coherent light field can be written as

a superposition of orthogonal fields, all mutually completely incoherent

and with powers given by the $\mu_m$

If we could measure this coherency/density matrix

i.e., establish all the fields $|\eta_m\rangle$ and eigenvalues (powers) $\mu_m$

we would have completely characterized the partially coherent field

retaining all "interference" information that is knowable from measuring average powers

# Measuring the coherency matrix

Though this representation of the coherency matrix has been known for some time

- the "natural mode" basis or the Karhunen-Loève representation
  - it has apparently not been known how to decompose onto this basis physically in general
    - or, equivalently, how to measure the full coherency matrix
      - Such a physical decomposition would also
        - separate the field into its mutually incoherent components

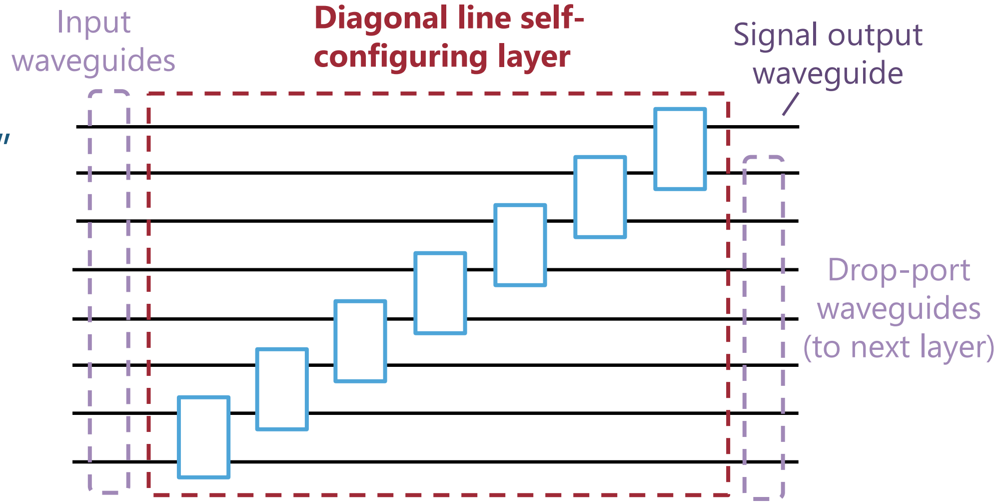
**We have figured out how to do this!**

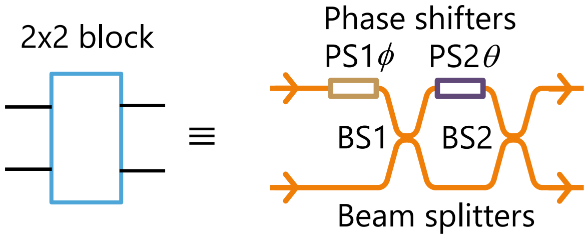
C. Roques-Carmes, S. Fan, and D. A. B. Miller, "Measuring, processing, and generating partially coherent light with self-configuring optics," Light Sci Appl **13**, 260 (2024).

# Self-configuring layers

"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013); "Self-configuring universal linear optical component," Photon. Res. **1**, 1 (2013); "Analyzing and generating multimode optical fields ... Optica **7**, 794 (2020)

- A self-configuring layer is a set of connected two-beam interferometers
  - topologically defined as
    - each input is connected to the "signal" output by one and only one path through the interferometer blocks
- Such self-configuring layers can be uniquely set up for a given input field
  - just based on physical power maximization at the signal output
    - optimally coupling the amplitudes in the input waveguides to the signal output



# Self-configuring layers

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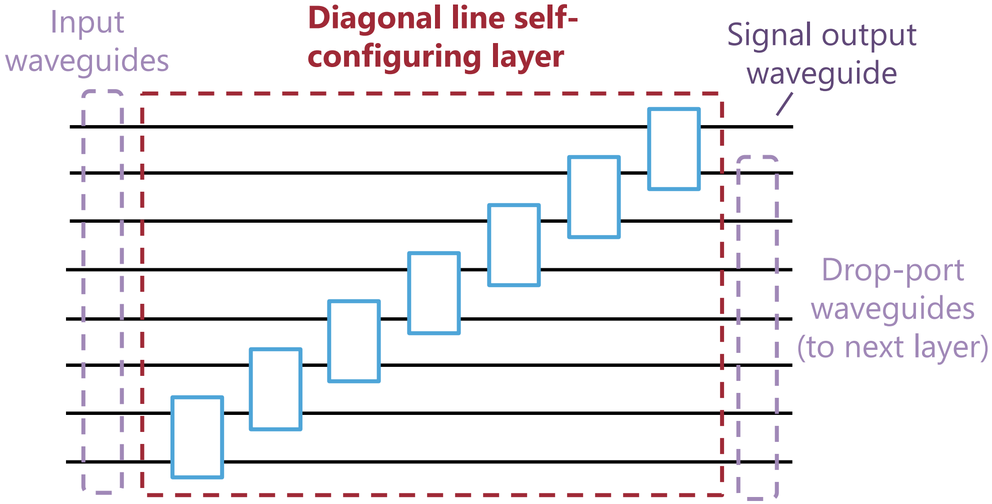
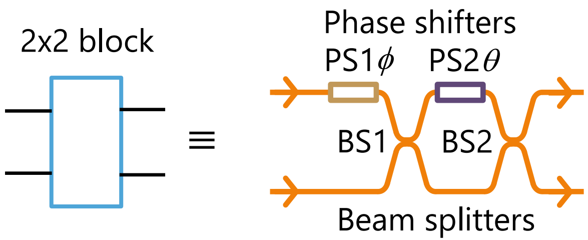
- For coherent light across the input waveguides
  - the algorithm is completely progressive
    - successively minimizing power at the drop ports of the interferometer blocks
    - by adjusting the phase shifters, one by one
- For partially coherent light, the algorithm would have to be a global optimization over all the phase shifters in the layer
  - for example, by stochastic gradient descent
- Note that this is a physical optimization in real time on the optics
  - not a separately calculated optimization applied to the phase shifters



# Self-configuring layers

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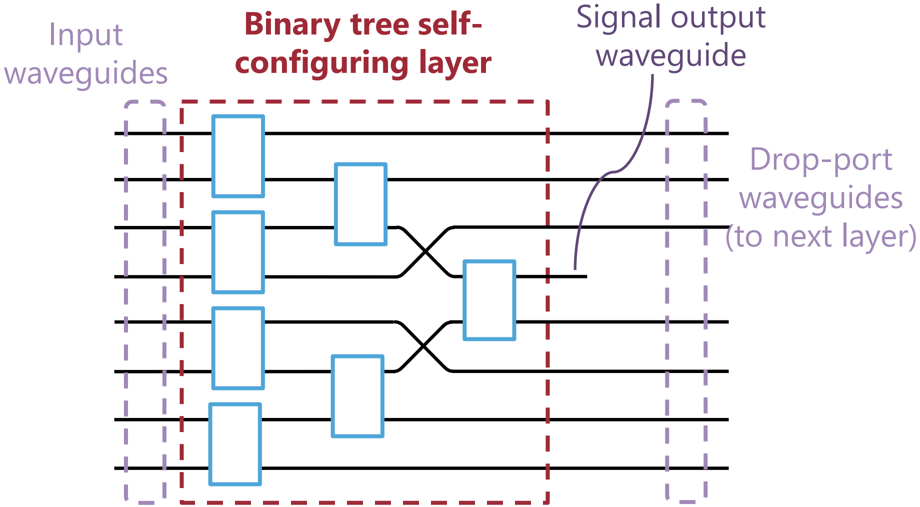
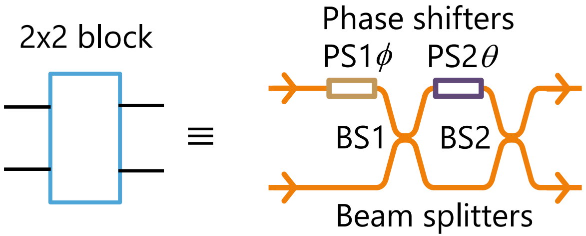
Other architectures

- such as the (symmetric) binary tree
  - still corresponding to the same topological definition
    - "each input is connected to the "signal" output by one and only one path through the interferometer blocks"

can also be used for the self-configuring layer

- and hybrids of the "diagonal line" and (symmetric) binary tree can be constructed
  - still obeying the topological requirement



# Measuring and separating partially coherent fields

To perform the measurement and separation of the partially coherent field

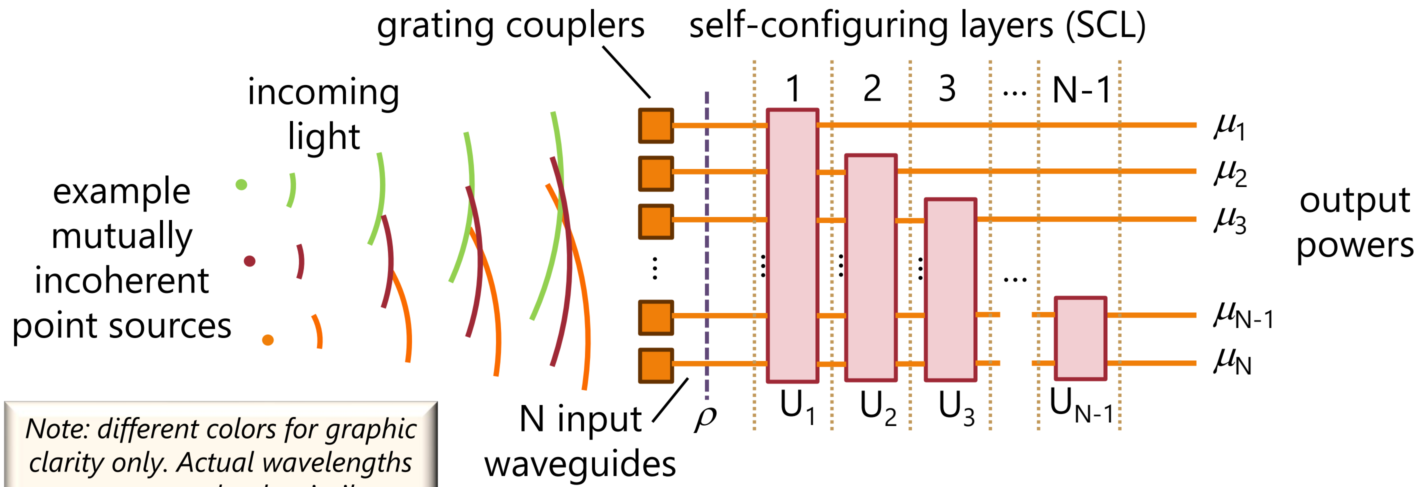
we construct a sequence of self-configuring layers (SCLs)

separating out a "signal" output to one waveguide

and passing the remaining waveguides to the next layer

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

A set of N-1 layers is sufficient to separate the field from N input couplers or pixels




*Note: different colors for graphic clarity only. Actual wavelengths are presumed to be similar.*

# Measuring and separating partially coherent fields

Configure SCL 1 to maximize output power $\mu_1$

Configure SCL 2 to maximize output power $\mu_2$

Configure SCL 3 to maximize output power $\mu_3$

...

Configure SCL N-1 to maximize output power $\mu_{N-1}$

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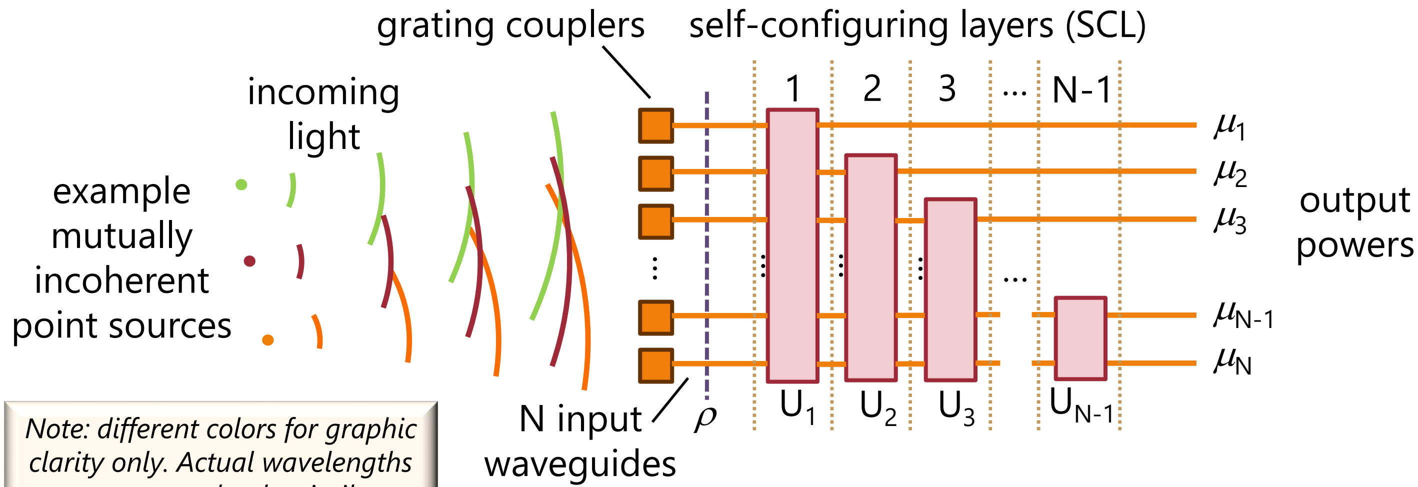


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# Measuring and separating partially coherent fields

Now the partially coherent field is fully measured

The powers are the eigenvalues of the coherency matrix

The settings of the interferometers in the self-configuring layers give the eigenvectors

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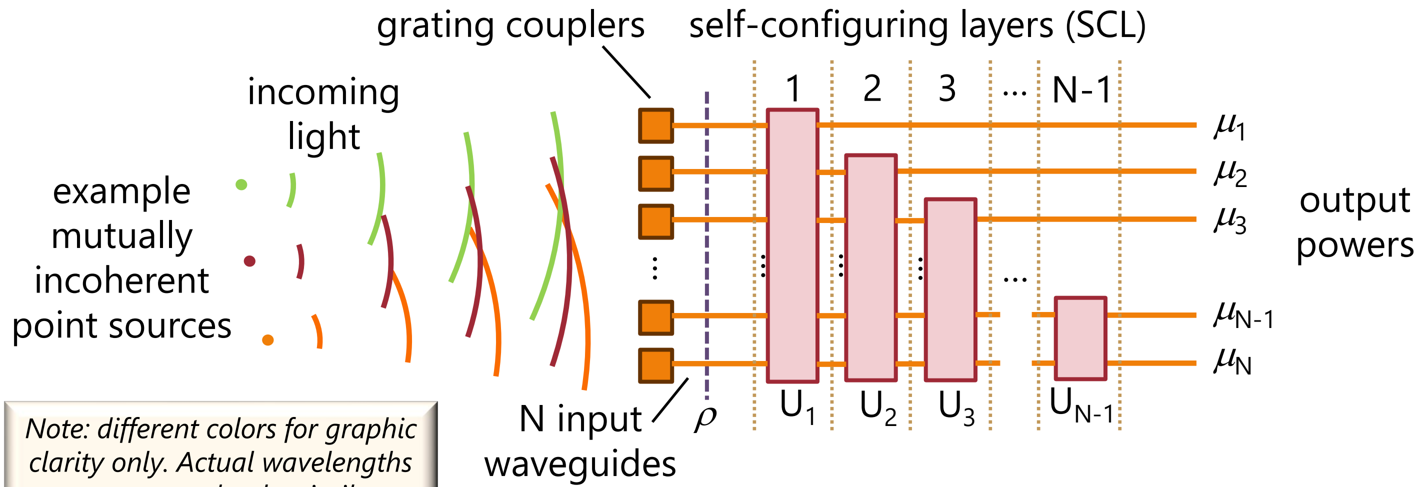


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# Measuring and separating partially coherent fields

The field has been physically separated into its mutually incoherent parts

There would be no "fringes" if we interfered the powers in any pair of output waveguides!

***We are not aware of any previous way of doing this***

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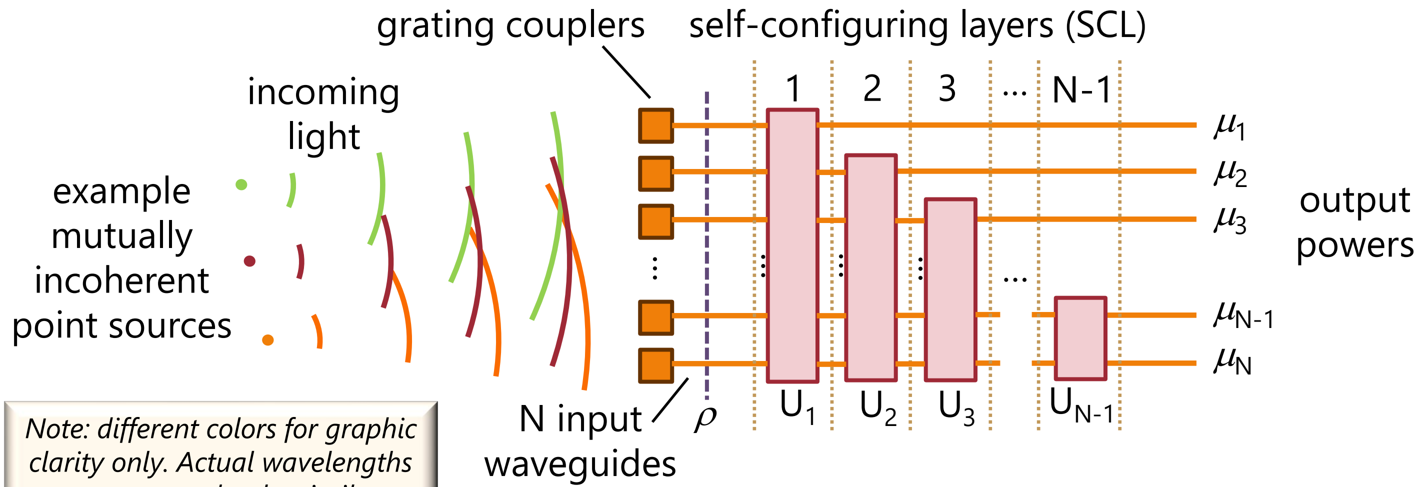


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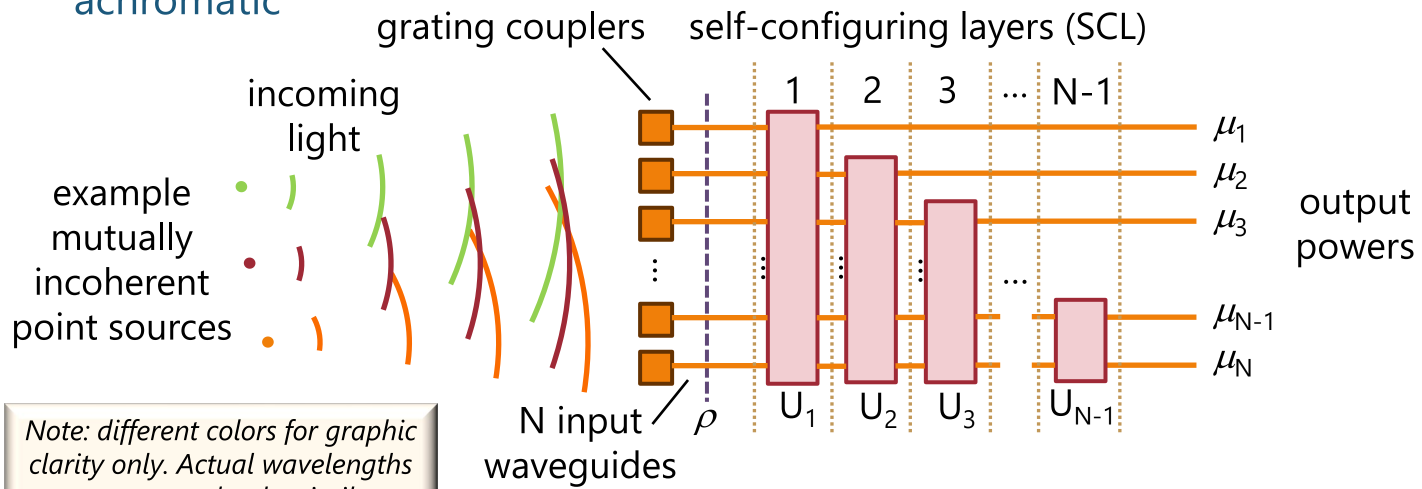
# Measuring and separating partially coherent fields

Note that this has obvious practical limits

- The number of “pixels” (grating couplers) cannot be large
  - needing a “layer” of interferometers for each pixel
- The practical spectral bandwidth is not large
  - because the interferometers are is only approximately achromatic

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

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# Measuring and separating partially coherent fields

However, for applications with small numbers of pixels

e.g., some astronomical applications operating near the diffraction limit of the telescope

such as exoplanet detection

this may be a practically interesting approach

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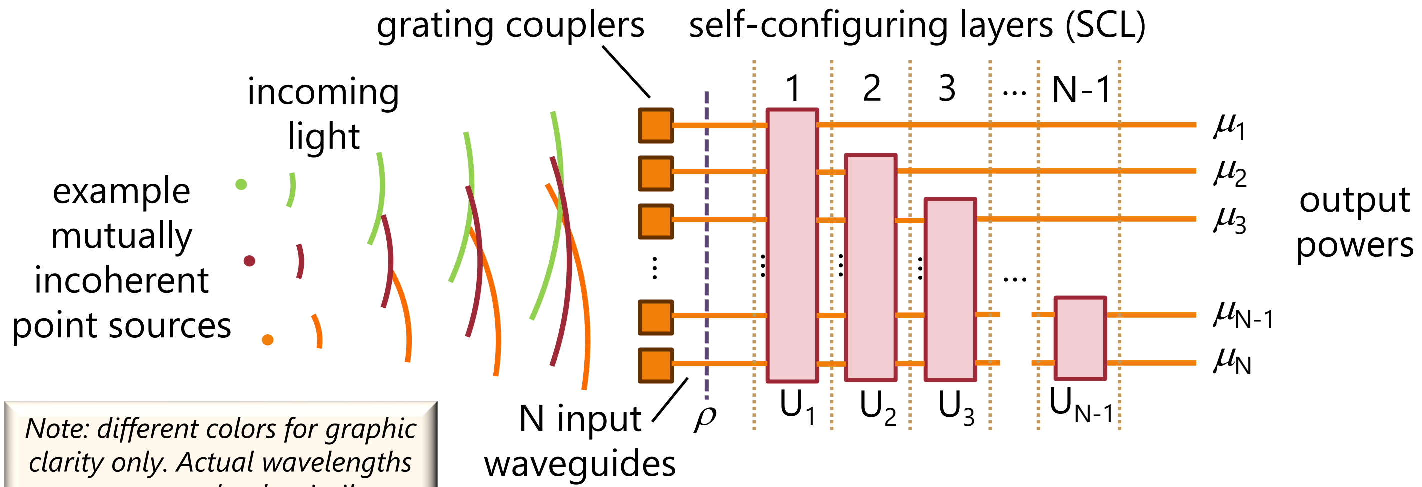


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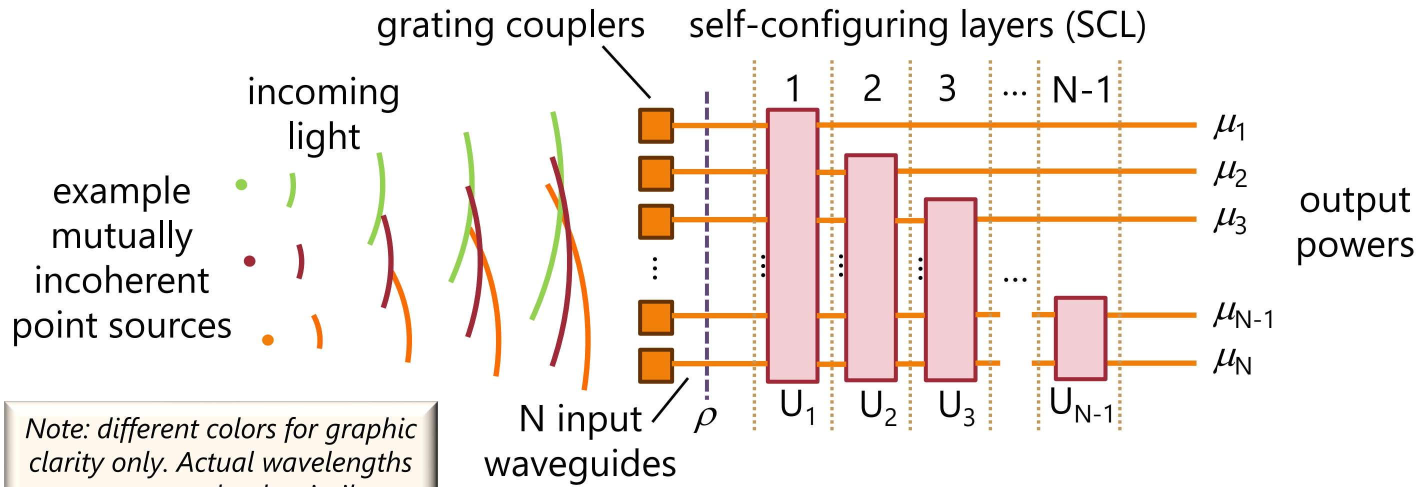
# Measuring and separating partially coherent fields

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

The approach may also be interesting in "thought experiments"
because it shows that there is in principle a loss-less machine
that can perform this physical separation

Such "thought experiment" uses of such meshes have already been useful
e.g., in proving Kirchhoff radiation laws including diffraction and non-reciprocity

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# Reconstruction of partially coherent volume fields

Suppose we use the mesh to measure a partially coherent field

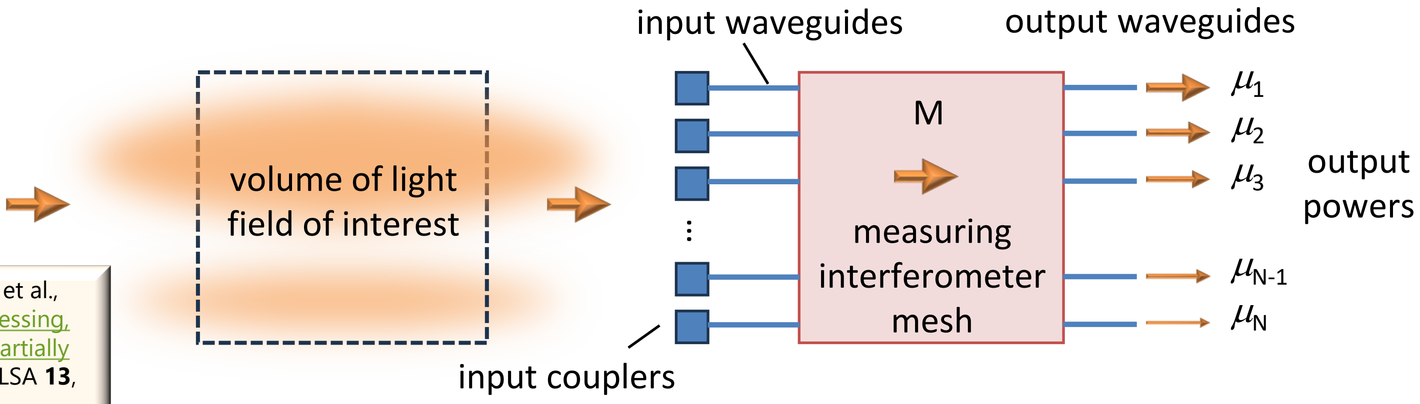
presuming this is all at approximately the same wavelength

noting the output powers and the interferometer mesh settings

Then, later on, after the input field has been removed

we can reconstruct it (in phase-conjugate backward form) by shining

mutually incoherent sources of the correct powers in backwards

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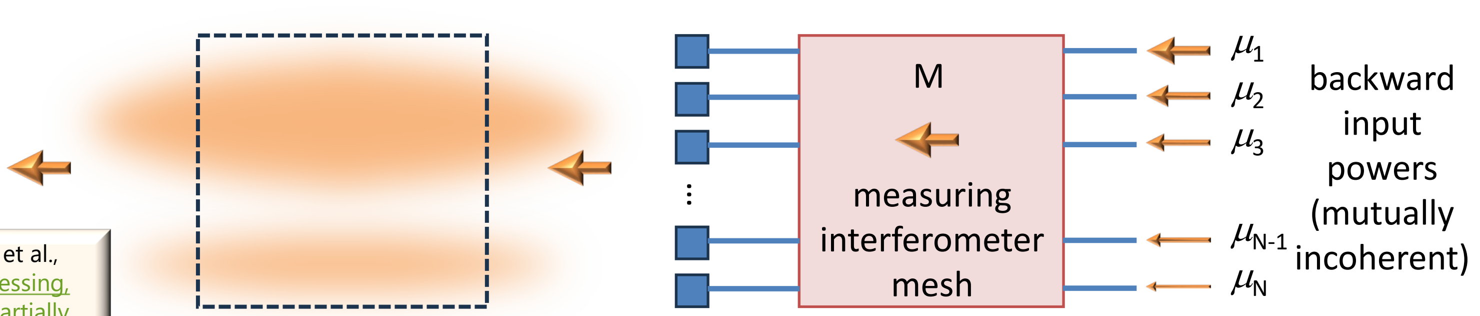
# Reconstruction of partially coherent volume fields

This will reconstruct the (phase conjugate of) the original volume field

(to the extent that the grating coupler arrangement could sense it)

We have effectively created multiple "holograms"

one for each "natural mode" component

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# Reconstruction of partially coherent volume fields

We could then scan an image sensor through the reconstructed field to form cross-sectional profiles of it

- without having to scan this sensor through the original field or "sample"

By turning on the backward powers one by one

- we could reconstruct the individual mutually incoherent components of the original field

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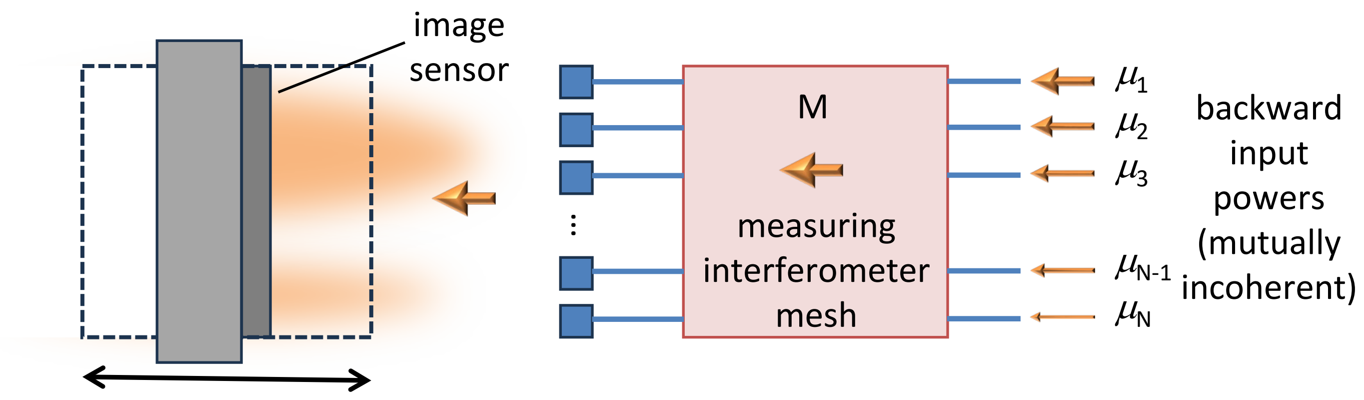


# Conclusions

We now know how to

- measure the coherency/density matrix of partially coherent light
- separate it physically into its mutually incoherent components

  the "natural modes" or Karhunen-Loève decomposition

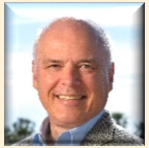
This is done using power maximizations with interferometer meshes

This means we have all the information to reconstruct the original field

  either mathematically or physically (in a phase conjugate form)

Such systems could be run backwards to recreate previously "recorded" partially-coherent volume light fields

Practical demonstration with existing interferometer meshes looks like it should be feasible



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