Self-configuring spectral filters by mapping time to space

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D. A. B. Miller, C. Roques-Carmes, C. G. Valdez, A. R. Kroo, M. Vlk, S. Fan and O. Solgaard

Universal programmable and self-configuring optical filter

"Forward-only" silicon photonic interferometer meshes

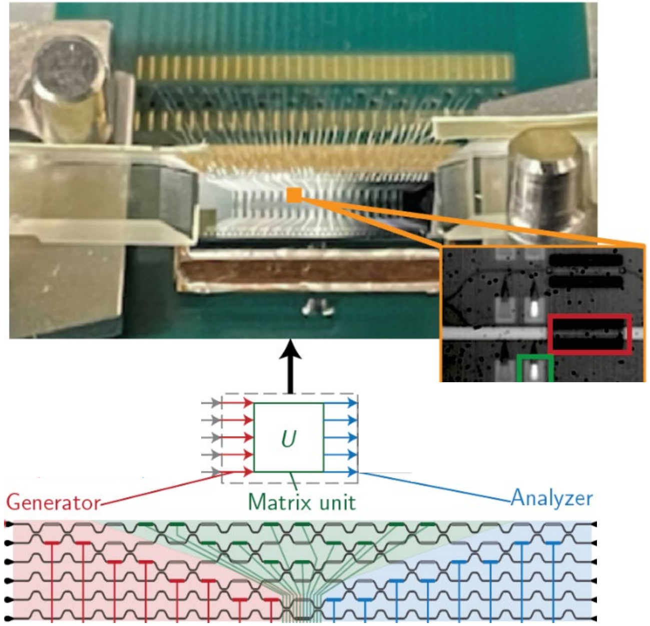
have proved very flexible and powerful for

- operating as matrix multipliers
- performing other mathematical operations
- sorting spatial modes

including self-configuring to problems with simple and powerful algorithms

even without calculations – e.g.,

- self-aligning beam couplers
- automatically separating partially coherent light



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

Universal programmable and self-configuring optical filter

Up to now such meshes have only been used for spatial applications

- essentially for one wavelength at a time
  - and not for any spectral use
    - such as separating beams of different wavelengths
      - or measuring spectral characteristics

Now we show how they can make programmable spectrometers

- including now demonstrations of
  - self-configuration to input wavelengths
  - arbitrary self-programmed filter functions
  - multiple simultaneous filter functions
- and proposals of
  - novel high-resolution spectroscopy with simple systems
  - measuring temporally partially coherent light and
    separating it into its mutually incoherent, mutually orthogonal components
      - the Karhunen-Loève decomposition
    equivalent to measuring the single-photon density matrix

"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," http://arxiv.org/abs/2509.12059

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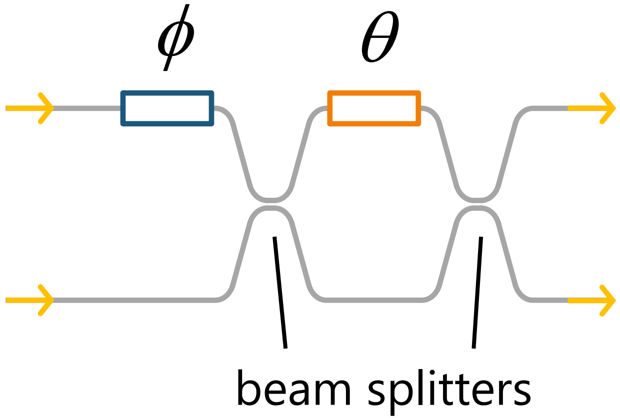
Self-configuring layers of interferometers

Nulling a Mach-Zehnder output

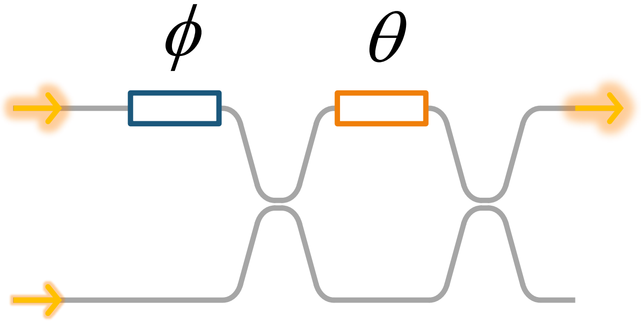
Consider a waveguide Mach-Zehnder interferometer (MZI)

- formed from two “50:50” beam splitters
- and at least two phase shifters
  - one, ϕ, to control the relative phase of the two inputs
  - a second, θ, to control the relative phase on the interferometer “arms”

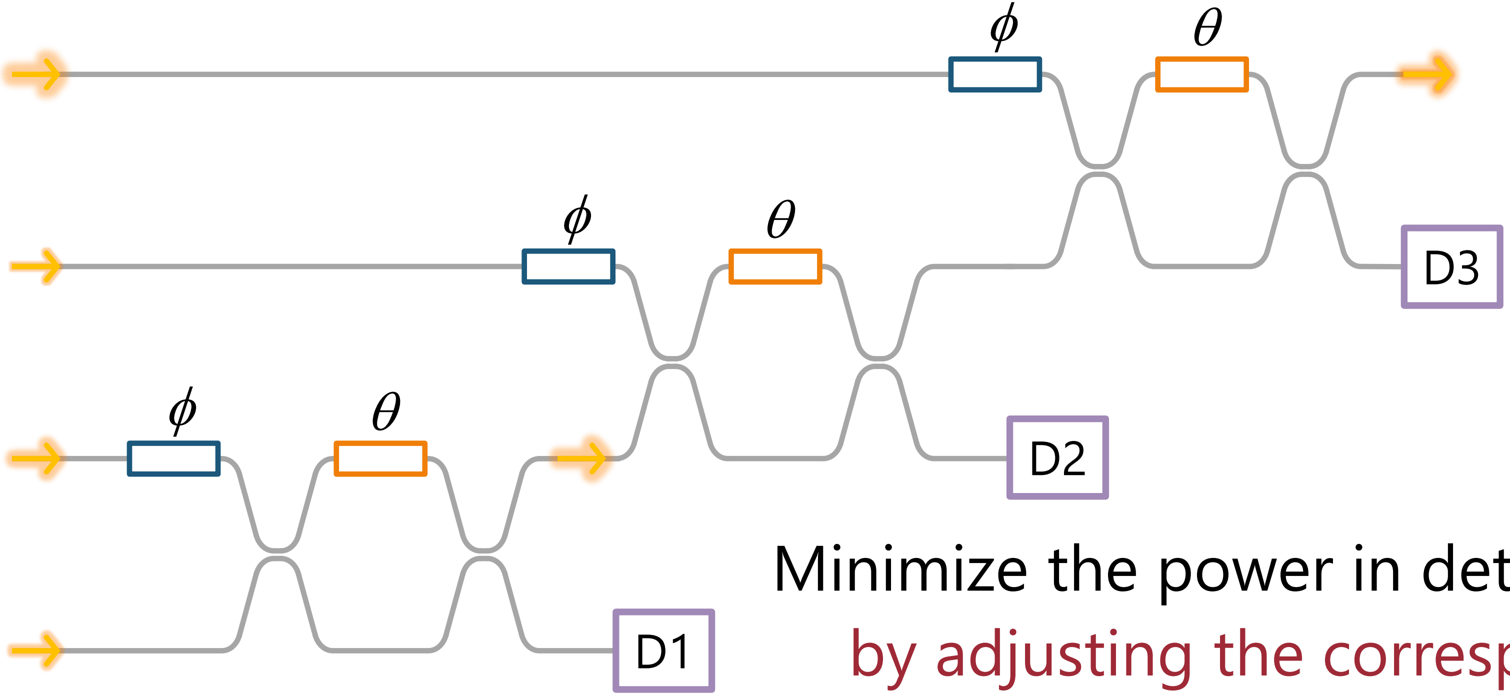


Nulling a Mach-Zehnder output

In such an MZI with 50:50 beamsplitters
- for any relative input amplitudes and phases
  - we can "null" out the power at the bottom output
    - by two successive single-parameter power minimizations
    - first, using ϕ
    - second, using θ



"Diagonal line" self-aligning coupler



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

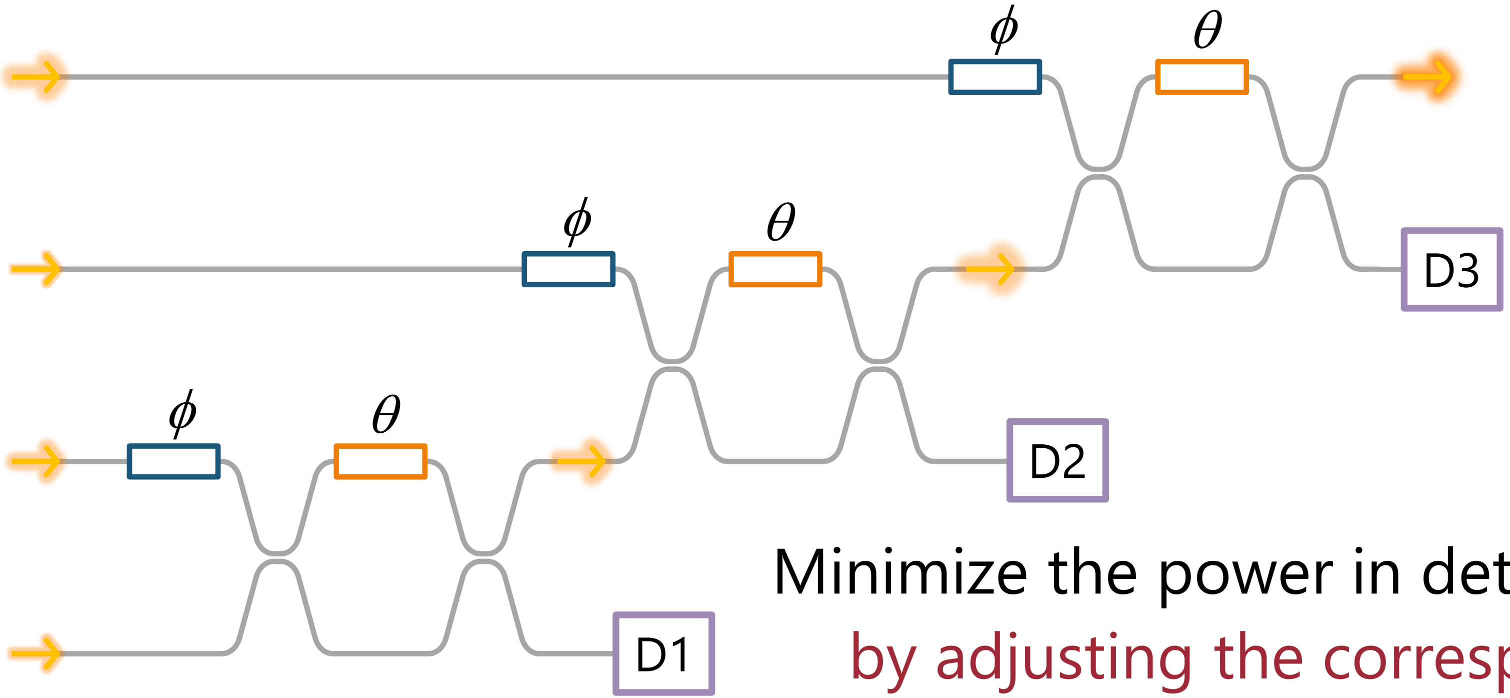
Minimize the power in detector D1

by adjusting the corresponding ϕ

and then θ

putting all power in the upper output

“Diagonal line” self-aligning coupler



Minimize the power in detector D2

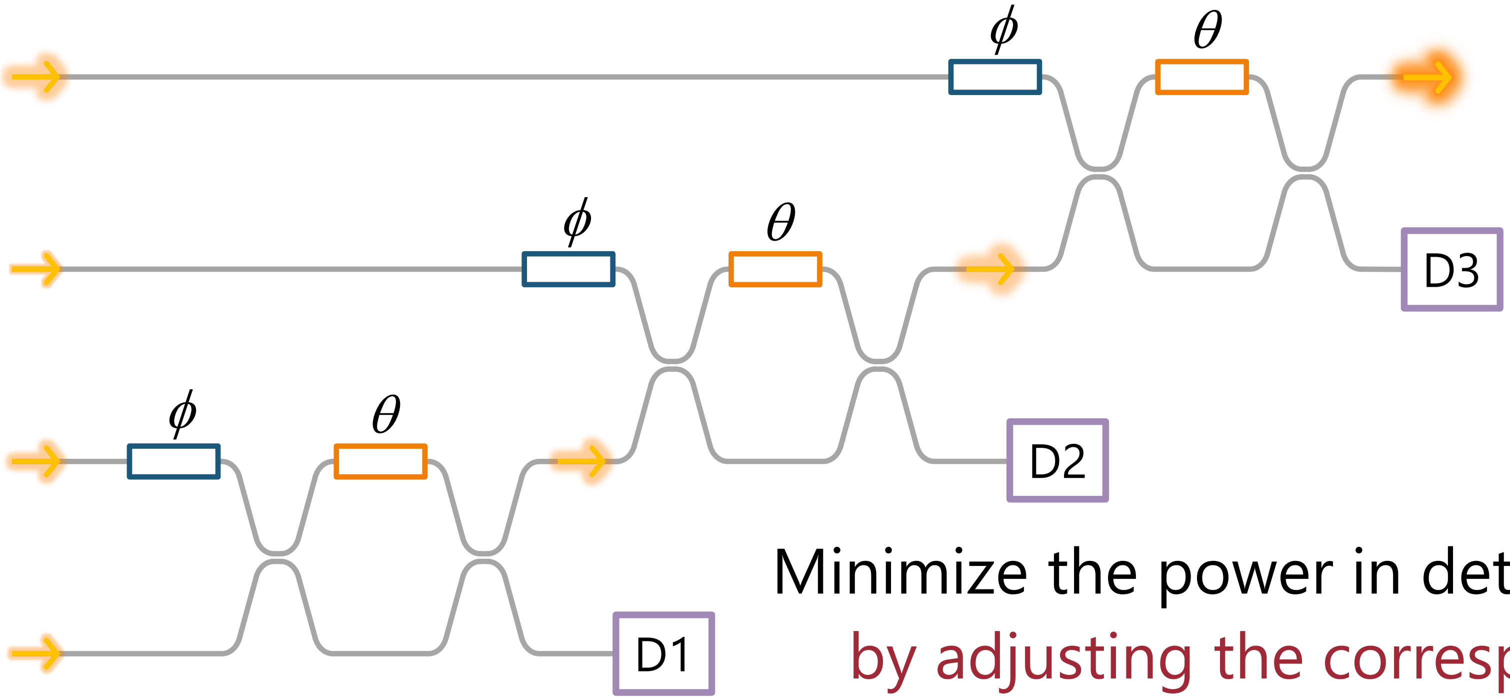
by adjusting the corresponding ϕ

and then θ

putting all power in the upper output

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

"Diagonal line" self-aligning coupler



Minimize the power in detector D3
by adjusting the corresponding ϕ
and then θ
putting all power in the upper output

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

Self-aligning beam coupler

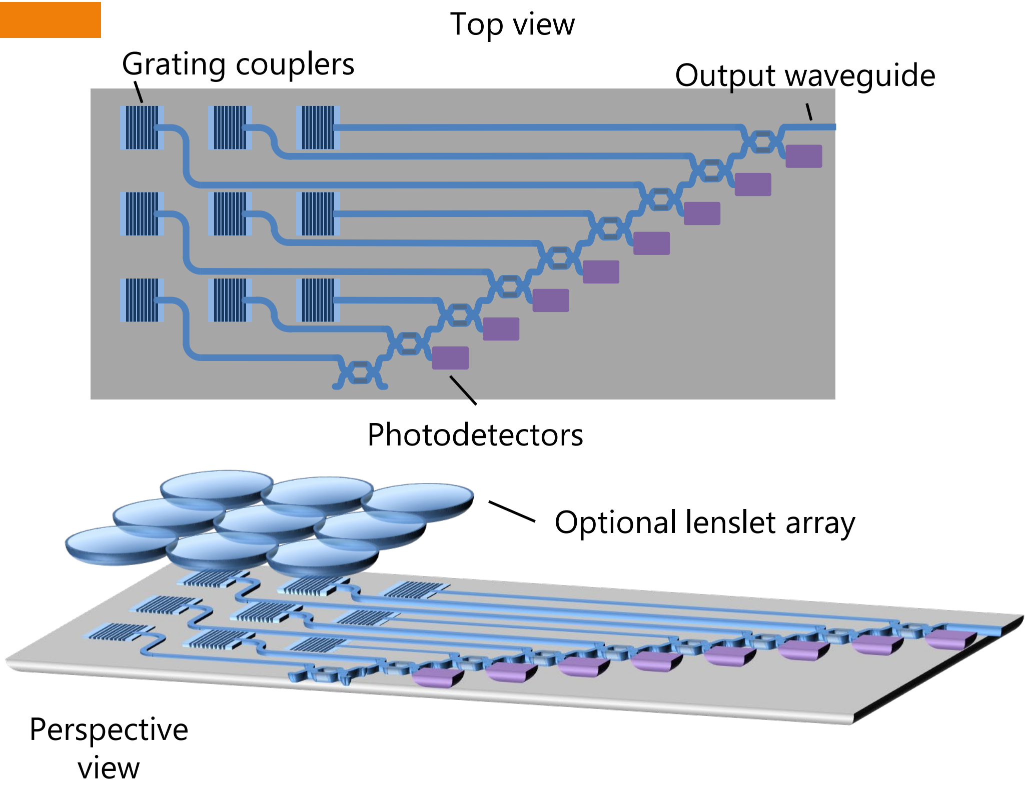
Grating couplers could couple a free-space beam to a set of waveguides

Then

we could automatically couple all the power to the one output guide

This could run continuously

tracking changes in the beam



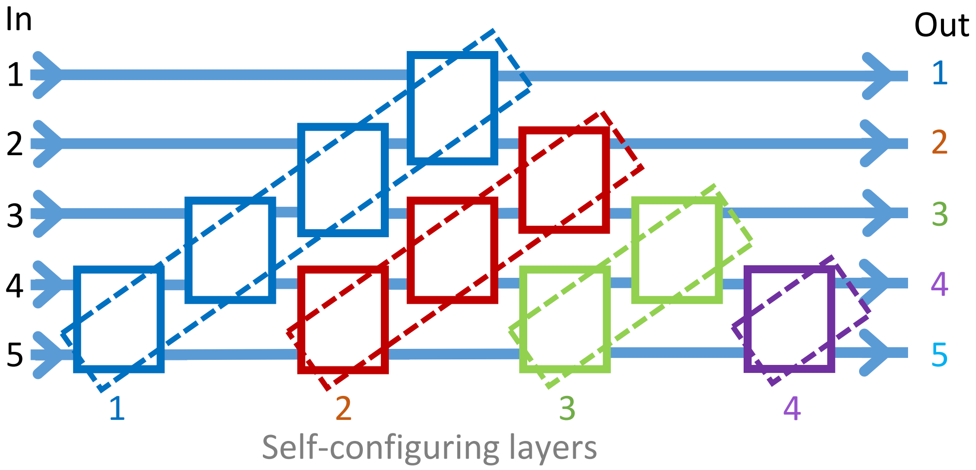
"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

Self-configuring layer topology

"Self-configuring layers" can also be defined topologically:

they have one (and only one) connection path through 2x2 blocks from their output to each of their inputs

For example, a complete "triangular" mesh can be viewed as being built from successive "diagonal line" self-configuring layers

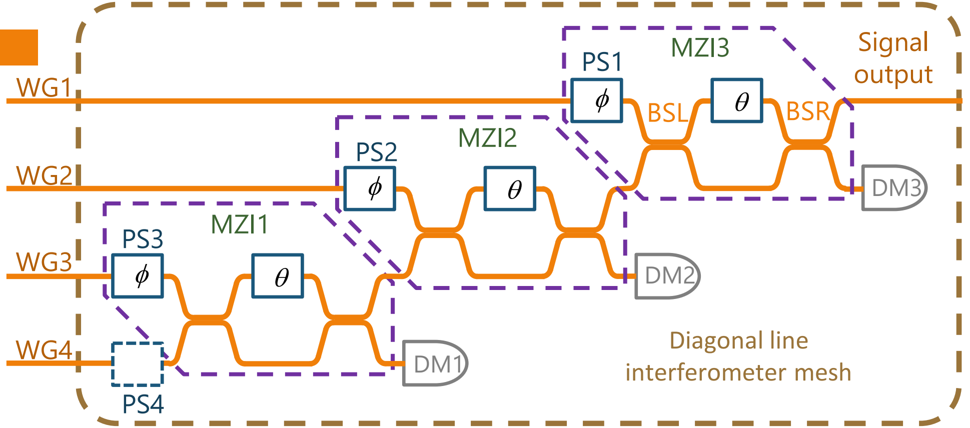


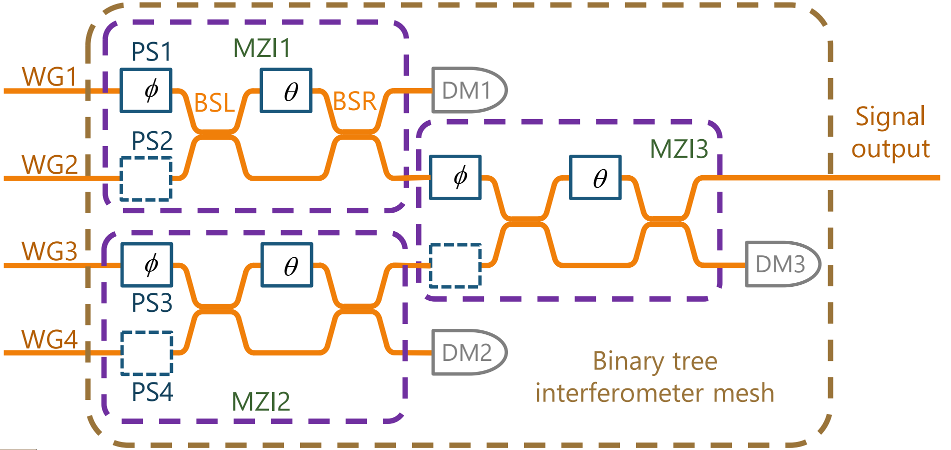
Not all mesh topologies support self-configuring layers

e.g., a "rectangular" mesh does not

Example self-configuring layers

Another form of self-configuring layer is the
- (symmetric) binary tree
  - which also obeys the same topology:
    - one (and only one) connection path from the output to each layer input
- Hybrids of diagonal line and binary trees are also possible
  - while obeying the same topological rule





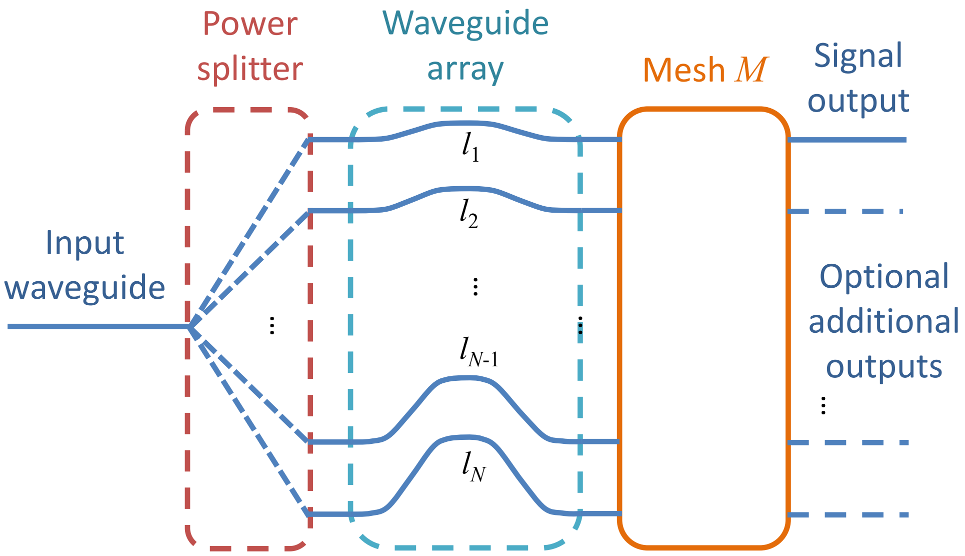
"Self-aligning universal beam coupler," Opt. Express **21**, 6360 (2013)

Self-configuring spectral filters

Basic spectral device concept

Power-split the light from the input waveguide into
- an array of waveguides of different lengths
  - similar to the waveguides in an arrayed waveguide grating (AWG)

The splitting and the waveguide array turn light of different wavelengths into
- different (spatial) amplitude vectors into the mesh
  - **mapping time to space**
  - The mesh then implements filter functions based on its programmed matrix M
    - giving one or more signal outputs
      - each with its own filter function
        - each programmable separately



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

Valdez et al., "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," http://arxiv.org/abs/2509.12059

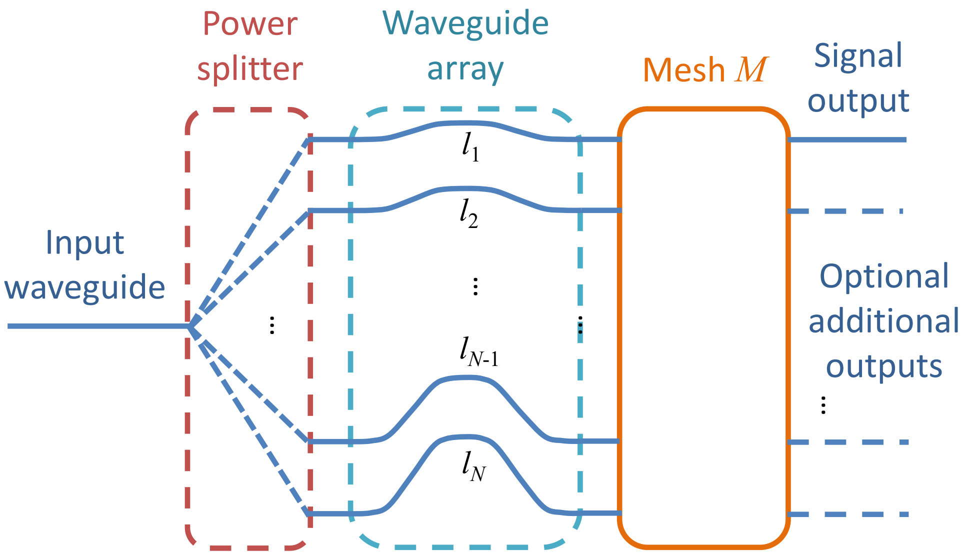
Basic spectral device concept

Just as for spatial meshes

- the device can self-configure
  - e.g., automatically aligning an input wavelength
    - to appear out of a signal output

Note too that the self-configuration can

- automatically compensate for imperfections
  - in precise waveguide lengths
  - allowing precise filters
    - with imprecise fabrication



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

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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

In a mesh with multiple successive self-configuring layers

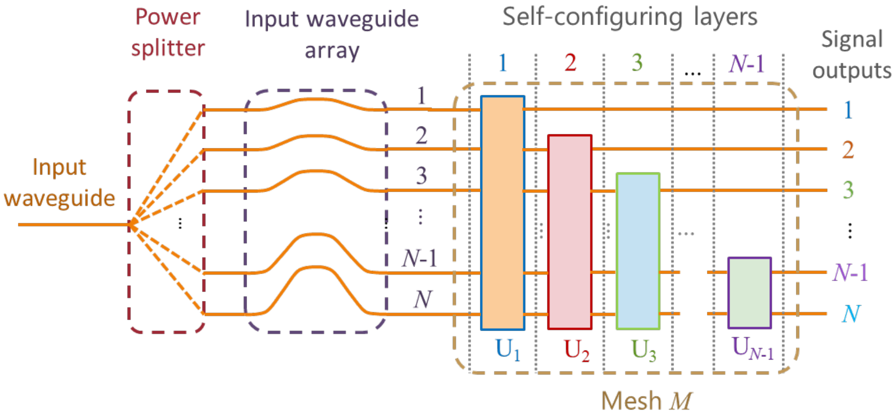
it allows multiple different simultaneous filter functions

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)

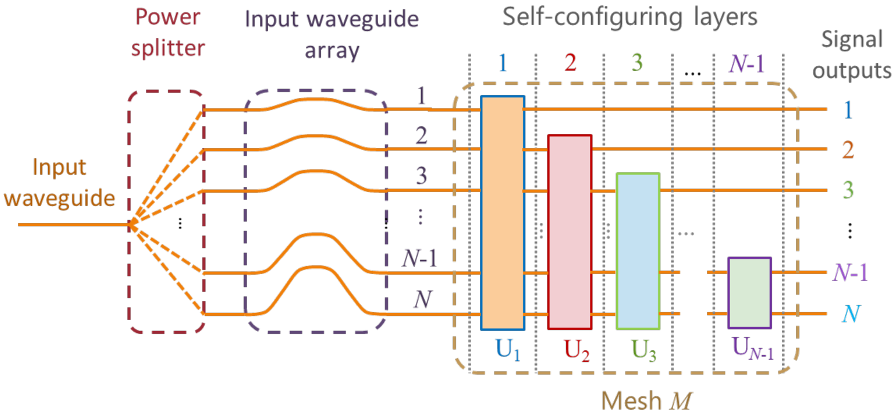


C. G. Valdez, A. R. Kroo, M. Vlk, C. Roques-Carmes, Shanhui Fan, D. A. B. Miller, and O. Solgaard, "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," http://arxiv.org/abs/2509.12059

Universal programmable and self-configuring optical filter

- We could combine with meshes working with the spatial degrees of freedom
  - for combined spatial/spectral programmable systems
- Possibly these ideas can be extended to other implementations
  - such as metasurfaces
- We have performed the theory and simulations of these device concepts
  - and are now reporting the first experiments

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)



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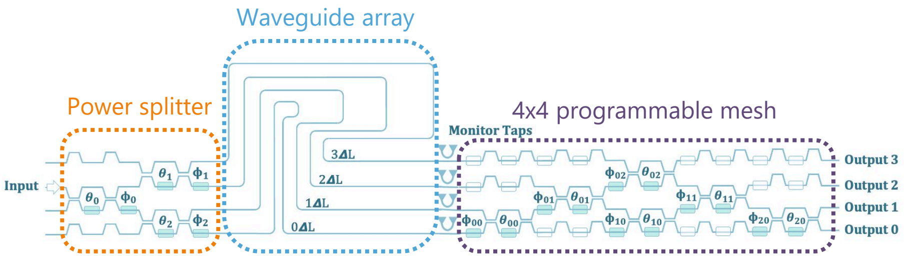
First experimental demonstrations

Programmable spectrometer test chip

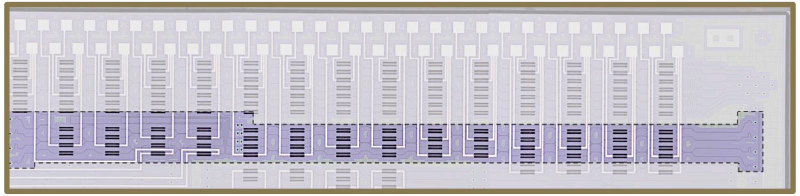
First test chip design

- binary tree for controllable power splitting between the guides
  - set to uniform splitting for these experiments
- 4 waveguides
  - with increasing uniform length increase ΔL between channels of 740μm
    - Corresponding designed free spectral range of 100GHz (~ 0.8nm)
- full 4x4 triangular unitary mesh for programming filter behaviors

Chip conceptual layout



Fabricated silicon photonic circuit



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Single-layer filter response

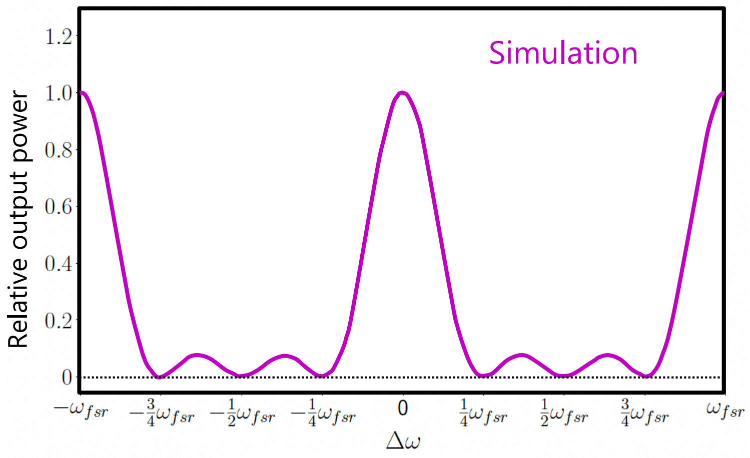
The filter shows response similar to one channel of an arrayed waveguide grating

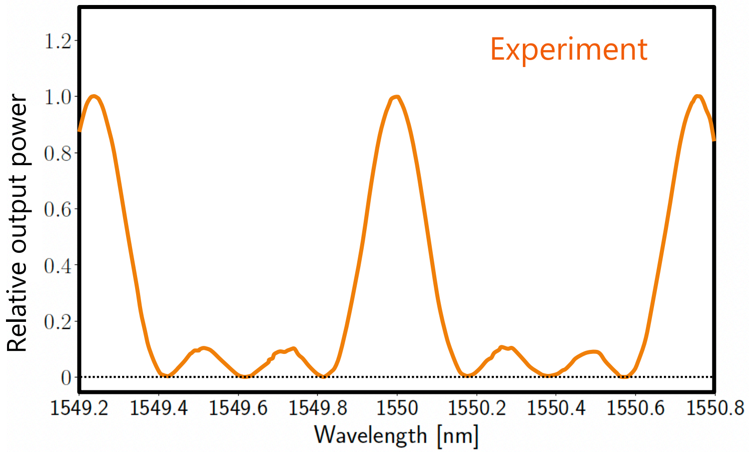
Analytic response: $e^{-j\frac{\Delta\omega\Delta t}{2}(N-1)}\frac{sinc(N\frac{\Delta\omega\Delta t}{2})}{sinc(\frac{\Delta\omega\Delta t}{2})}$

Minima show rejection of 28 to 30 dB.

This filter also self-configures to the center wavelength

and is easily tuned over the entire free-spectral range (FSR)





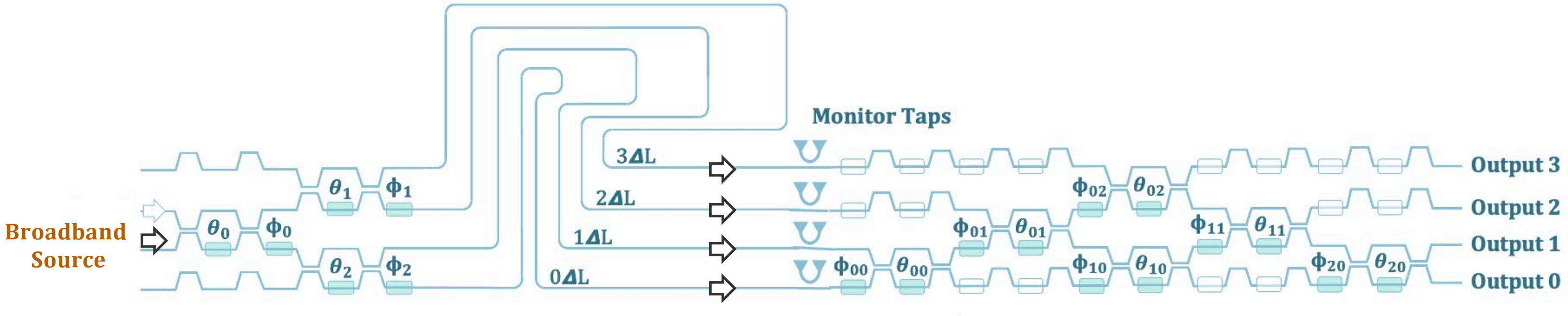
Tunable center wavelength

We may introduce a wavelength independent phase profile between channels using either:

The ϕ_i phase shifters in the power splitter

The ϕ_{0i} phase shifters in the first layer of the mesh

We apply a linear phase ramp with slope $2\pi\gamma$ where $\gamma \in [0,1]$



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

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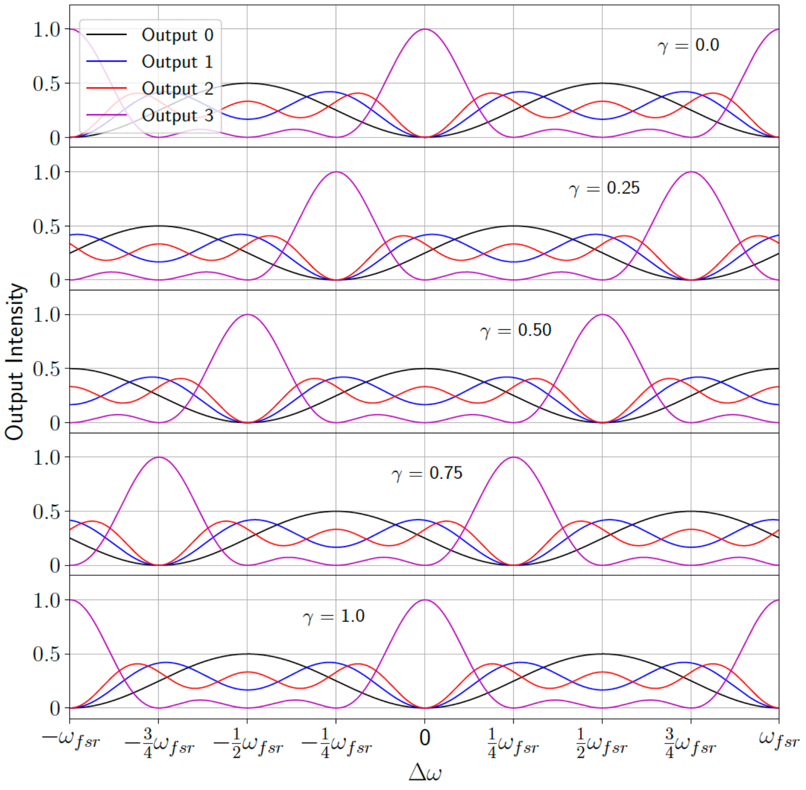
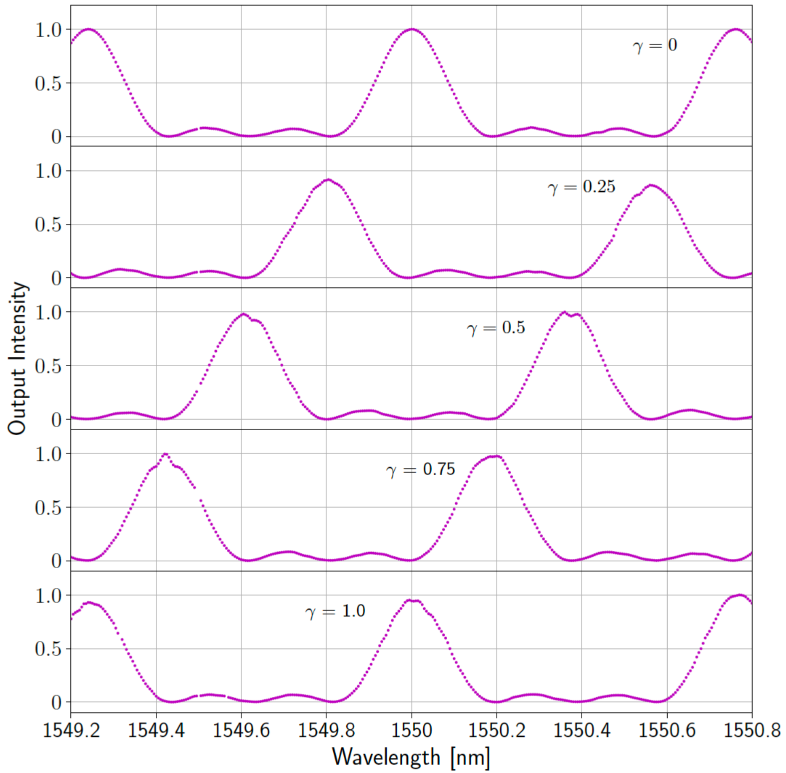
Tunable center wavelength

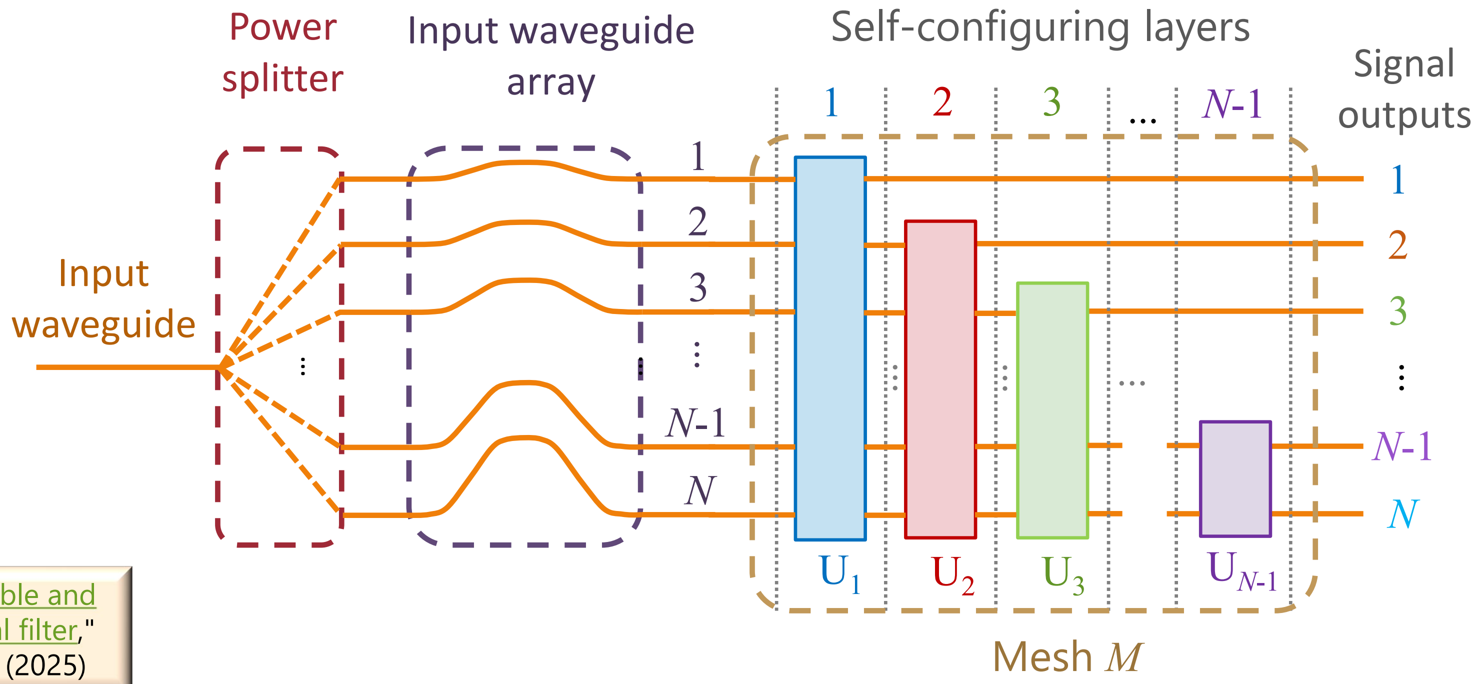
Simulation



Experiment



Multiple layer filter



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Valdez et al., "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," http://arxiv.org/abs/2509.12059

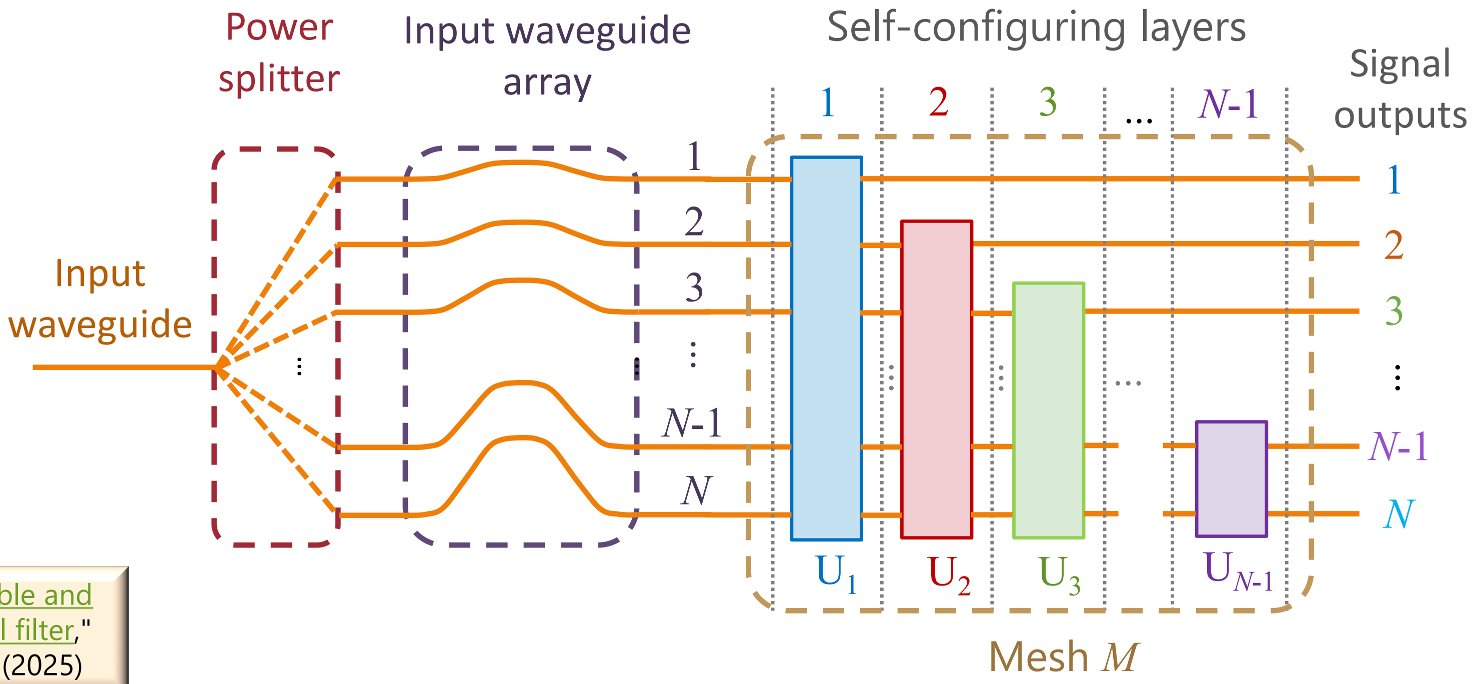
By cascading multiple (self-configuring) layers

we can simultaneously construct multiple arbitrary orthogonal filters

each with their own output

each of which can be self-configured

Rejection filter



"[Universal programmable and self-configuring optical filter](#)," Optica **12**, 1417-1426 (2025)

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The mesh can be self-configured to reject any N-1 wavelengths

leaving the remainder in output N

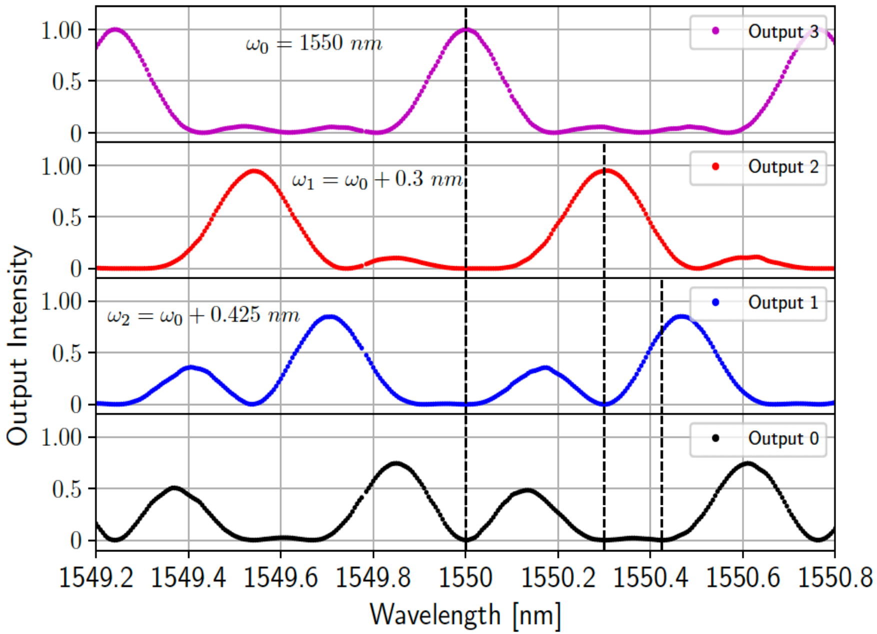
This rejection works for *any* such N-1 wavelengths

They need not "line up" with the "comb" of orthogonal waveguide array filters

Arbitrary wavelength rejection

- Each layer of the mesh may reject 1 arbitrarily chosen wavelength from the remaining outputs of the filter
- Measured contrast between 35dB and 4 dB for each of the filtered wavelengths

$\lambda_0 = 1550\text{nm} \mid \lambda_1 = 1550.3\text{nm} \mid \lambda_2 = 1550.425\text{nm}$



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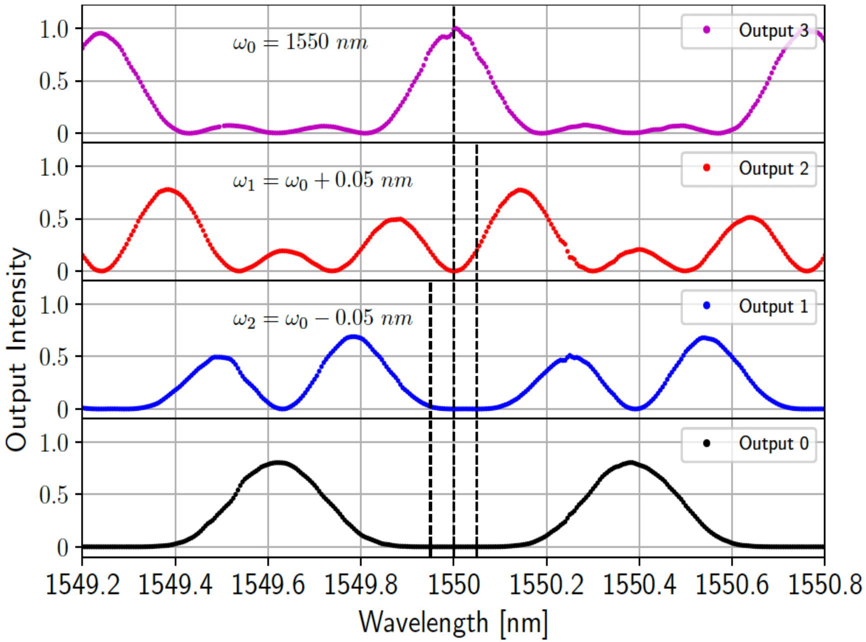
Rejection band filter

- We can place additional constraints of the pilot sources
- Here we choose wavelengths close together to form a wide rejection band
- Output 0 exhibits over 40 dB of rejection over 13% of the FSR

λ_0 = 1550nm | λ_1 = 1549.95nm | λ_2 = 1550.05nm



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Wavelength division demultiplexing

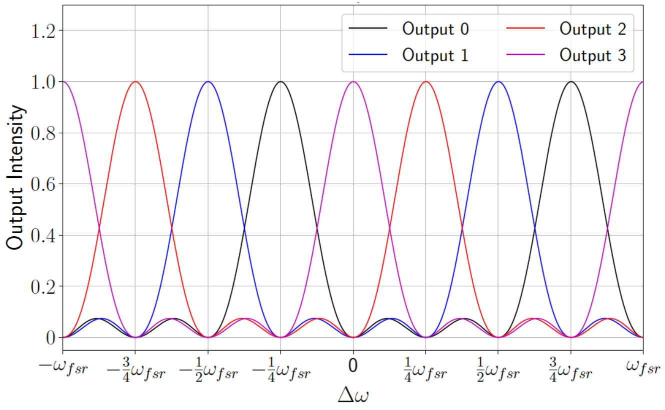
By choosing pilot source wavelengths to correspond to the "AWG" filter minima

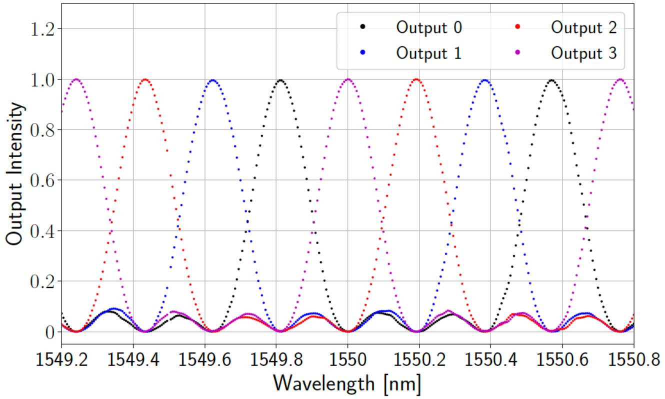
this filter gives perfect transmission of a single wavelength to each channel

Inter-channel crosstalk is between -25 dB and -40 dB

This emulates the functionality of an arrayed waveguide grating with a 23.75 GHz channel spacing.

Valdez et al., "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," http://arxiv.org/abs/2509.12059

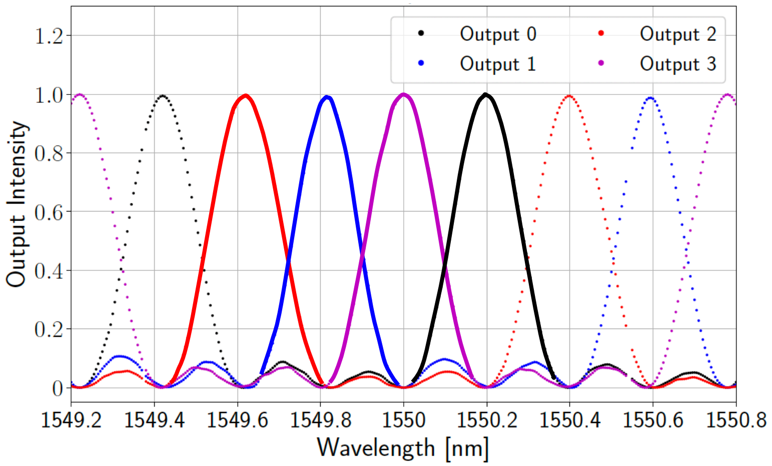


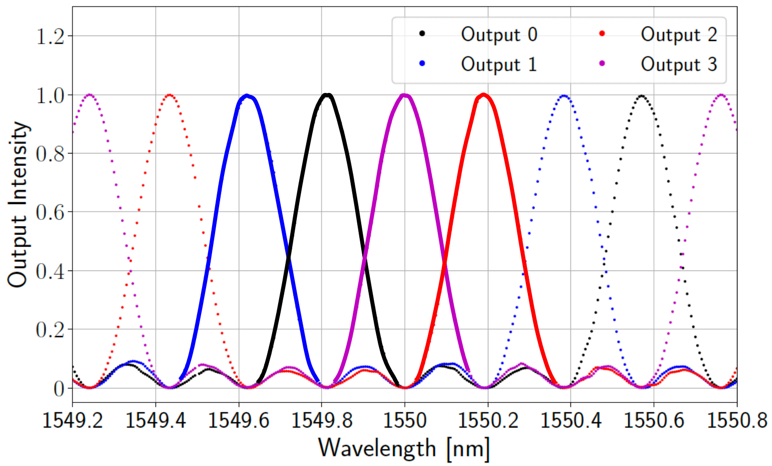


Any wavelength to any output

In typical AWGs the channel mapping is determined at fabrication

The channel mapping of this device may be reconfigured by changing the sequence of pilot sources used for self-configuration





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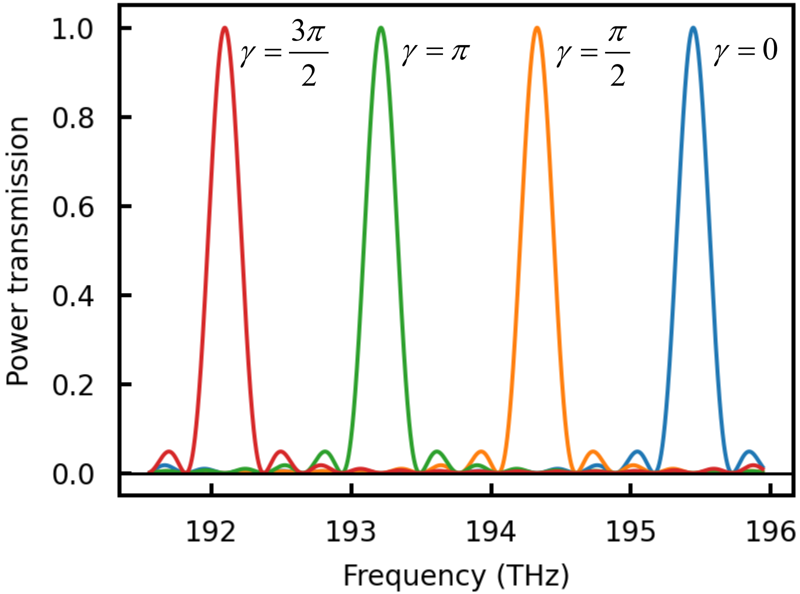
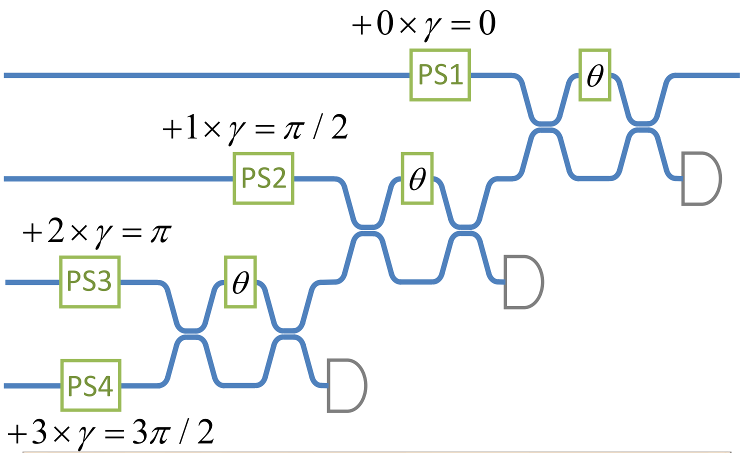
Simulated spectral response of 16 waveguide filter

Simple filter with $N = 16$ waveguides



Additional phase delays for $\gamma = \pi / 2$
phase "tilt" for $N = 4$ waveguides



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

16 waveguide filter designed to operate usefully over a frequency range approximately equivalent to the telecommunications C-band, with waveguide lengths differing by increments of 16.51 microns

here configured to have one specific wavelength fully emerge from the layer output

The device can be tuned by adding "phase tilts" to the input phase shifters

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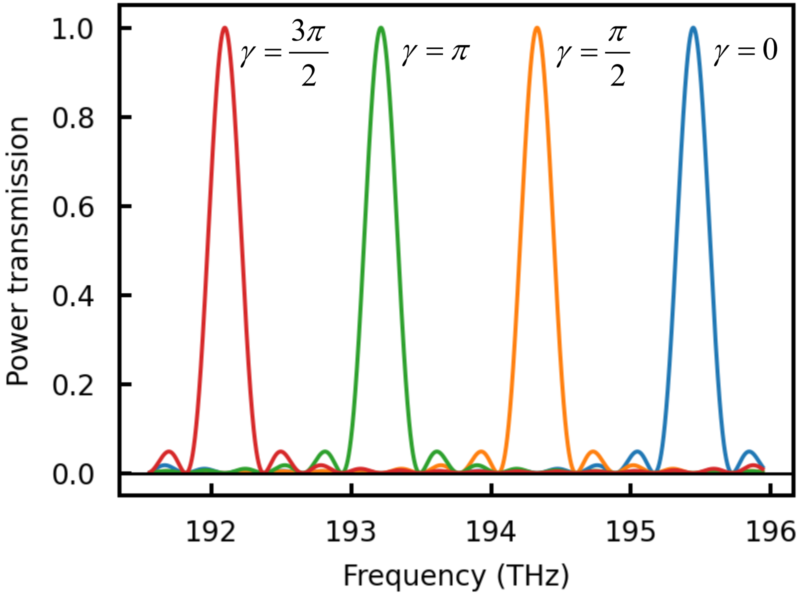

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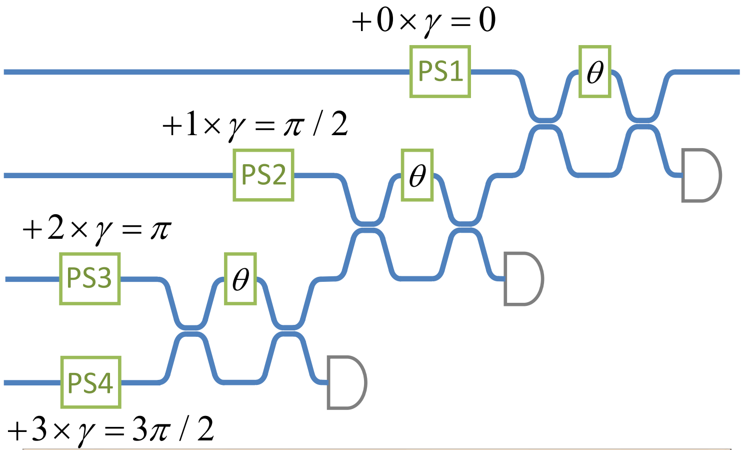


"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

This figure essentially shows 4 of 16 possible orthogonal filter functions

Any filter function that is a linear combination of those 16 can also be programmed

Proposed non-redundant array filters

Non-redundant array filter

"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

One trick to get very high resolution and reasonable spectral range
- but with only a moderate number of waveguides
  - is to use a "non-redundant array"

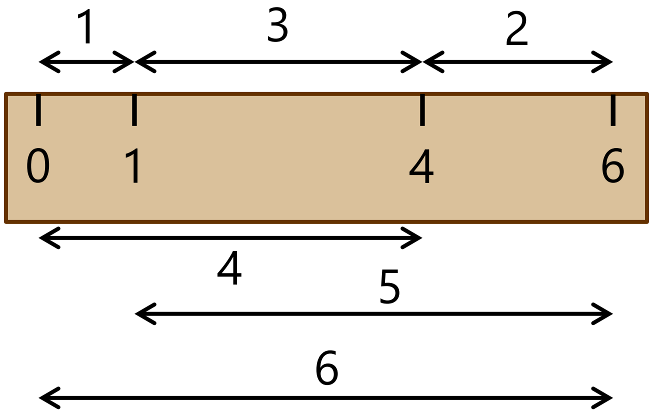
In such an array
- the length difference between any two waveguides differs from
  - the length difference between any other two waveguides
- which means their interference patterns in wavelength tend not to add constructively
  - though there can be a wavelength at which everything adds up
    - giving a narrow spectral response
      - with a width characteristic of the largest waveguide length
        - and a spectral range characteristic of the shortest waveguide (incremental) length

The price for this combination is that the rejection is not perfect at other wavelengths

Non-redundant array filter

One approach to "non-redundant" waveguide lengths is a "Golomb ruler"

- e.g., on a ruler with markings at 0, 1, 4, and 6
  - each pair of markings is separated by a unique distance
    - and in this "perfect" Golomb ruler
      - all separations from 1 to 6 exist
        - but only once



A Golomb ruler with only 4 markings that can measure all integer distances from 1 to 6 units

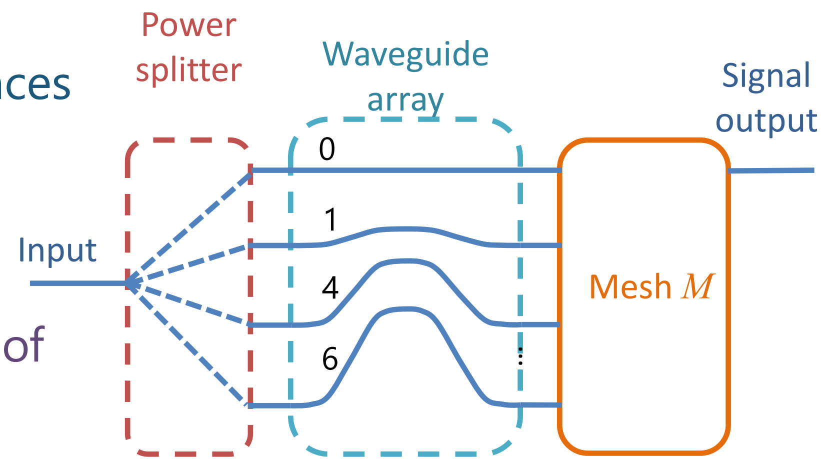
"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

Non-redundant array filter

Instead of using different positions on a line
- we can use different lengths of waveguides
  - as given, for example, by Golomb ruler distances

In our case, for this "4 element" Golomb ruler
- we could make relative waveguide lengths of
  - 0, 1, 4, and 6
    - instead of requiring 7 different waveguides of each integer length

Then we can set the phases for adding the waveguide outputs so that
- at one wavelength the fields add constructively
  - giving a sharp spectral response
    - characteristic of the total length difference in the set of waveguides



This array with only 4 waveguides may have a similar resolution to one with 7 waveguides

"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

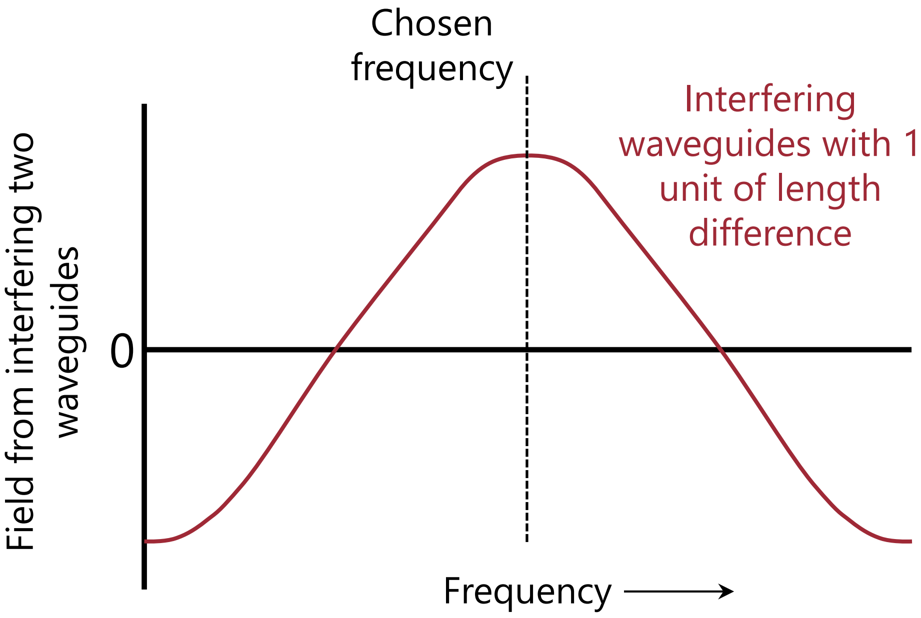
Non-redundant array filter

Key point: the “interference patterns” from summing the field from any two waveguides

- i.e., the sinusoidal frequency response from that pair
  - will all have different frequency periodicities
    - so they will generally not all add up
      - mostly approximately cancelling overall

But, by choice of the relative phases

- we can make them add near one specific chosen frequency



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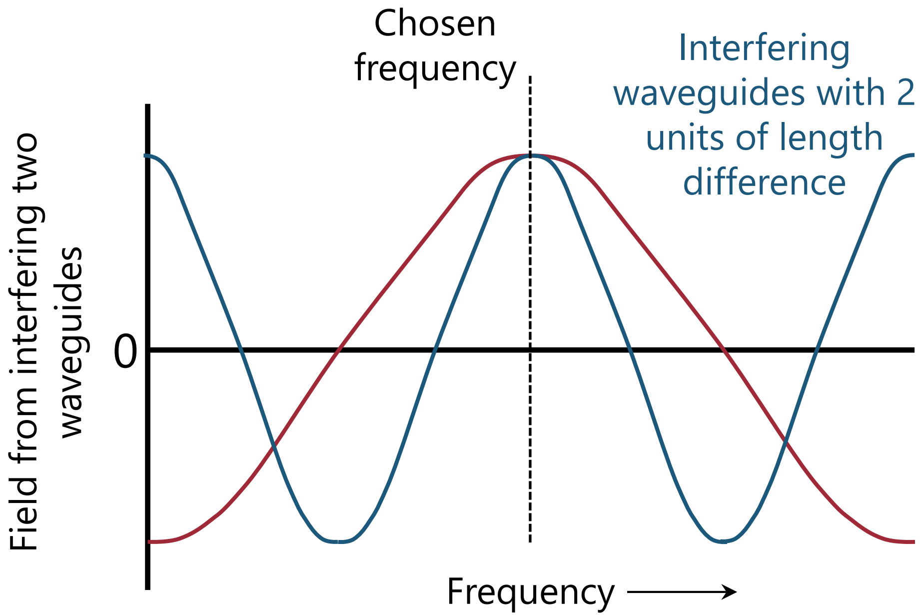

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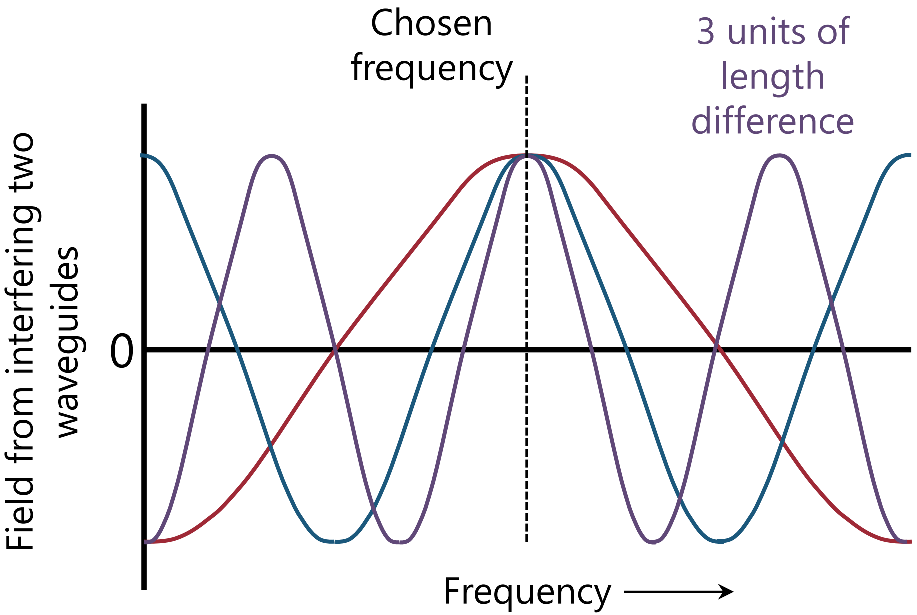
- we can make them add near one specific chosen frequency



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

Non-redundant array filter

Key point: the “interference patterns” from summing the field from any two waveguides

- i.e., the sinusoidal frequency response from that pair
  - will all have different frequency periodicities
    - so they will generally not all add up
      - mostly approximately cancelling overall

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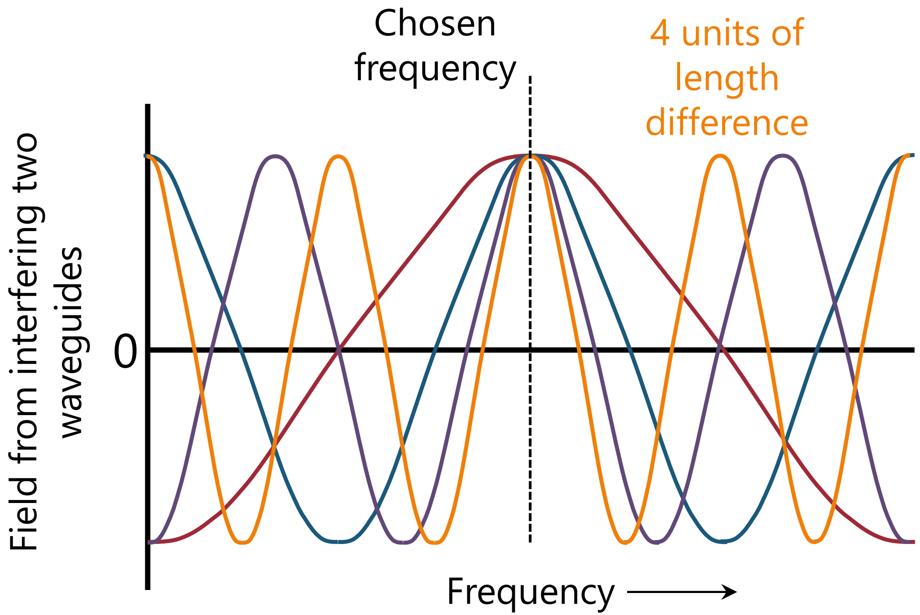

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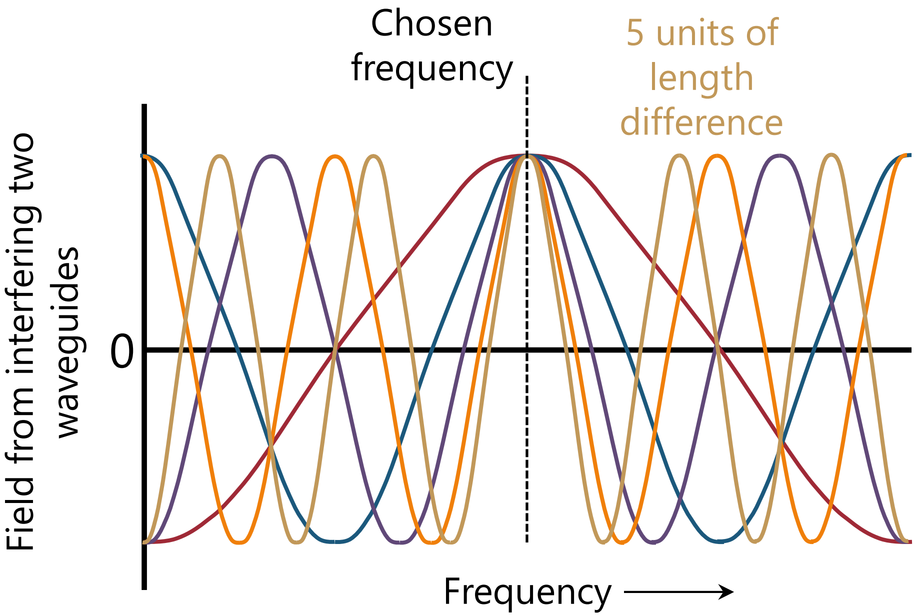

"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

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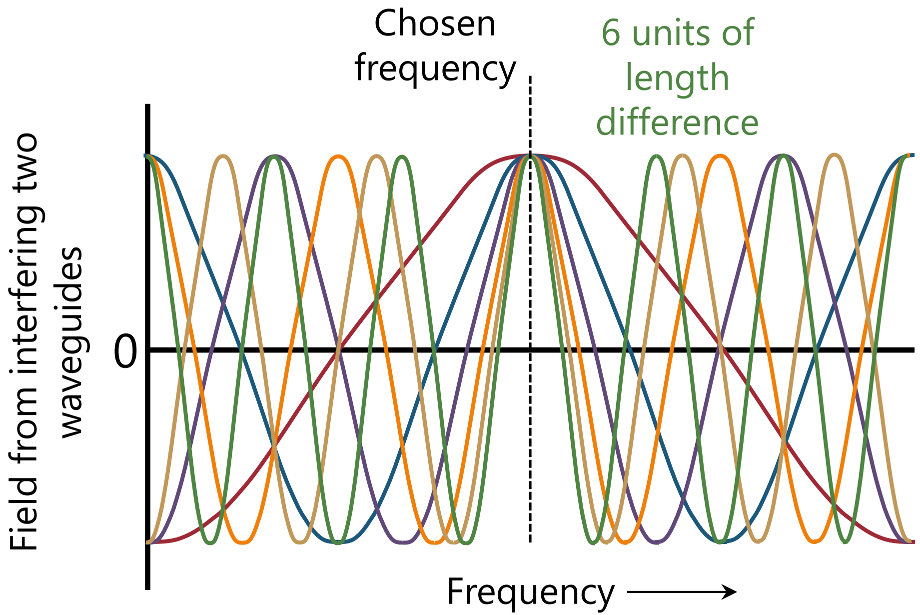

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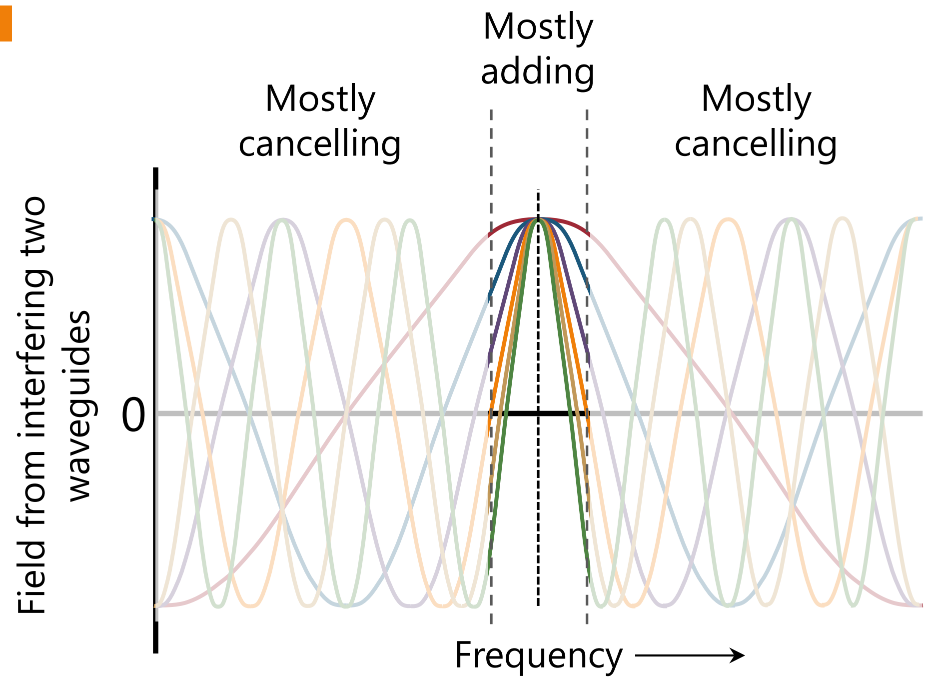
But, by choice of the relative phases
- we can make them add near one specific chosen frequency
  - with approximate cancellation at other frequencies



"Universal programmable and self-configuring optical filter," Optica **12**, 1417-1426 (2025)

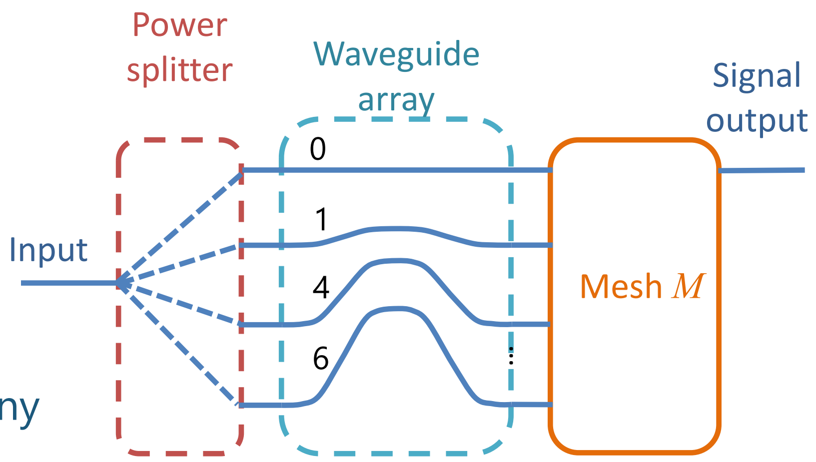
Non-redundant array filter

An (imperfect) Golomb ruler set of relative lengths for 16 guides would be
- 0,1,4,11,26,32,56,68,76,115,117,134,150,163,168,177

Though only having 16 waveguides
- this might have a similar resolution to one with 178 waveguides

To repeat
- For different non-redundant array waveguide lengths
  - the frequency response "interference patterns" of any pair of waveguides as a function of frequency
    - generally do not add up constructively
      - except that, at one set of waveguide phases
        - we can make them add up at one specific frequency

The price is imperfect rejection of other wavelengths



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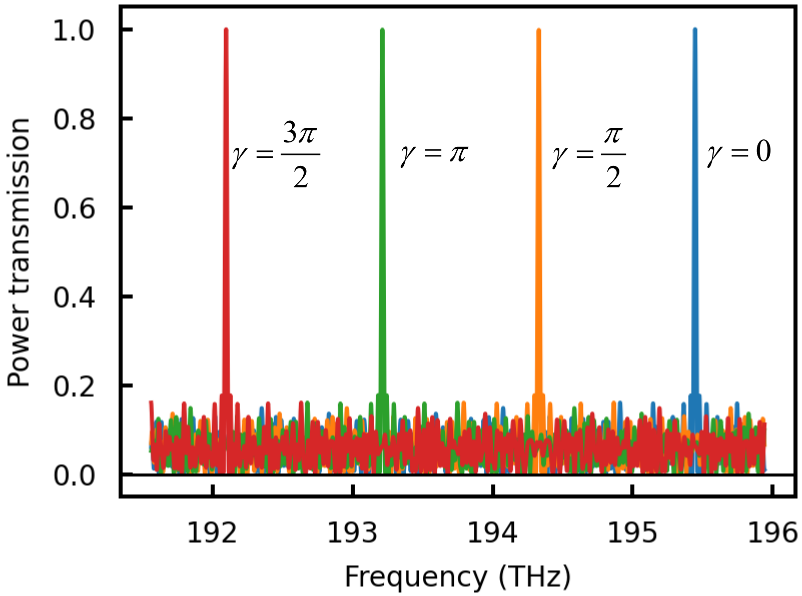
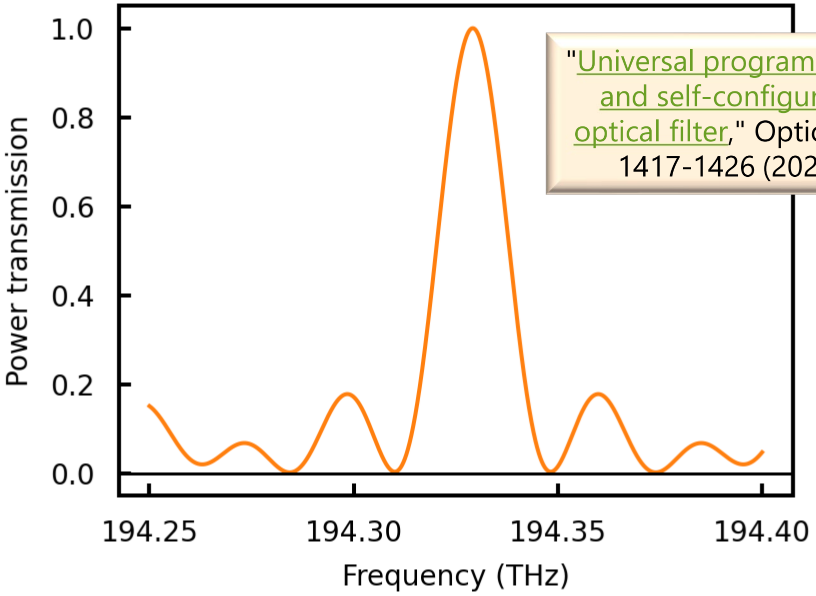
Simulated non-redundant array 16 waveguide filter

Non-redundant array filter with $N = 16$ waveguides



Expanded view of (c) ($\gamma = \pi / 2$ spectrum)



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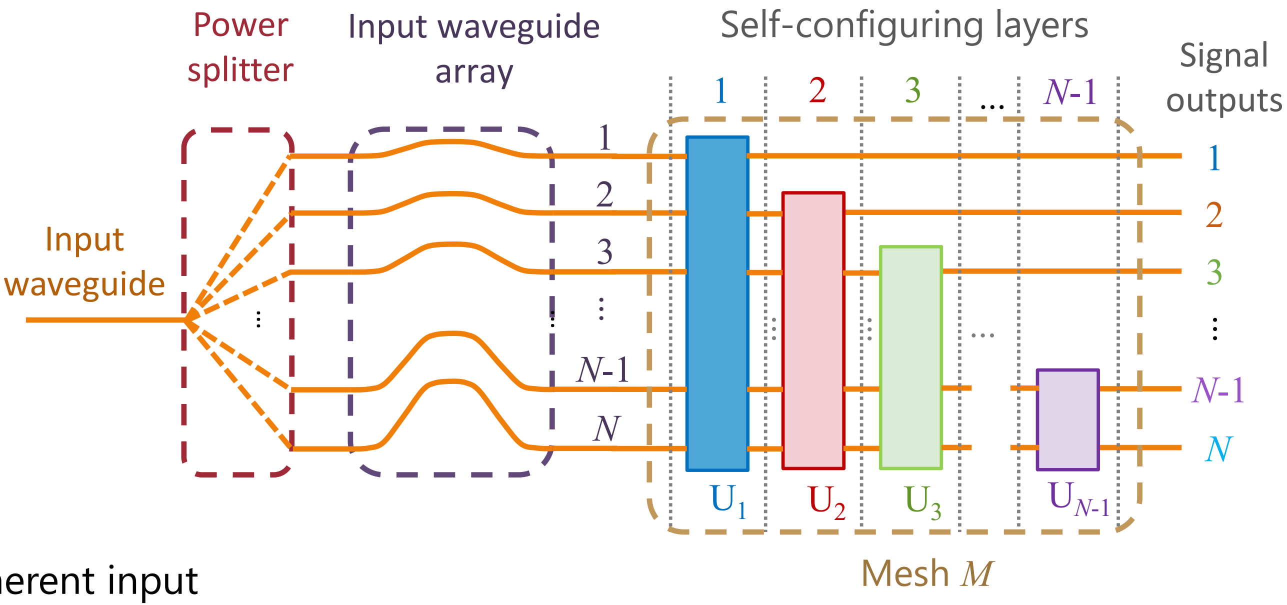
16 waveguide non-redundant array filter designed with waveguide lengths differing by "Golomb ruler" multiples of 16.51 microns to give a free-spectral range like the telecommunications C-band

The device can also be tuned by adding "phase tilts" to the input phase shifters

Measuring and separating temporally partially coherent light (or measuring the temporal single-photon density matrix)

Measuring and separating partially coherent light



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With partially coherent input

and power-maximizing on the signal outputs of each successive layer

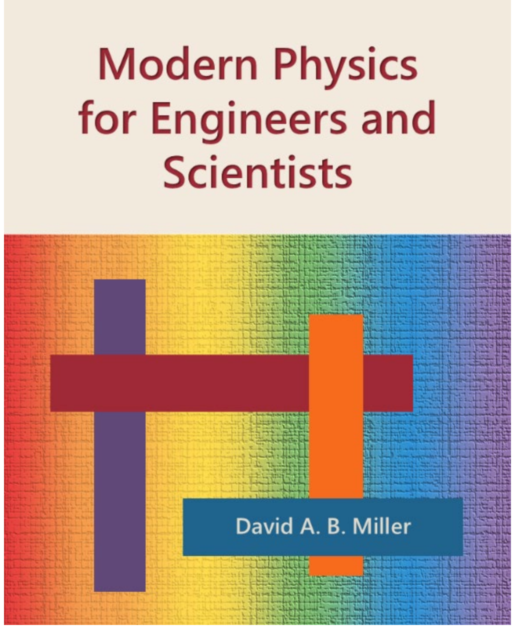
the temporal coherence function of the input light can be measured

and the light will be separated into its mutually incoherent orthogonal parts

a physical Karhunen-Loève decomposition (apparently not possible before)

Equivalent to measuring the single-photon density matrix of the light in the temporal domain

Modern Physics for Engineers and Scientists



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Free materials for an introductory modern physics class

- suited for engineers and scientists broadly
- covering quantum mechanics and statistical mechanics and their applications

A complete textbook, freely available online

- including extensive questions, problems, and solutions

A complete set of lecture videos and slide copies

- freely available for streaming or download
- linked from the textbook

Use

- as a textbook for a conventional lecture course
- for a “flipped classroom” course with students watching the online videos
  - with class time for discussion and solving problems
- for self-study, individually or in groups

Conclusions

- We propose that forward-only interferometer meshes
  - can also perform arbitrary spectral filtering by
    - feeding them with an array of waveguides of different lengths
- Benefits include
  - self-configuring filters
  - relaxation of precision of waveguide fabrication
    - because the phase shifters can compensate for that
  - novel and arbitrary filter functions
  - multiple simultaneous different filters
  - rejection of multiple arbitrary wavelengths
  - high-resolution filters using non-redundant array waveguide lengths
  - measuring temporal partial coherence
    - separating into Karhunen-Loève components
- First experiments successfully demonstrate complex and multiple simultaneous filter functions
- Can we can extend these ideas to metasurface or metastructure devices
  - e.g., by illuminating at an angle?
  - e.g., using multiple layers?

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