Self-configuring complex photonic circuits

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Self-configuring silicon photonics

Specific architectures can correct, stabilize, and configure themselves using simple progressive algorithms with local single-parameter feedback loops and can adapt to the problem in real time.
Applications

These meshes give optical systems that are universal in a way that is beyond previous optics. They open new opportunities in sensing, communications, and information processing, e.g., neural networks solving equations in both classical and quantum systems.
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, $\phi$, to control the relative phase of the two inputs, a second, $\theta$, to control the relative phase on the interferometer “arms”
Nulling a Mach-Zehnder output

Suppose we shine (mutually coherent) light into both interferometer inputs with possibly different amplitudes and phases.

We can adjust $\phi$ to minimize the power at, say, the bottom output.
Nulling a Mach-Zehnder output

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We can adjust $\phi$ to minimize the power at, say, the bottom output.

The fields from the two inputs are now in “antiphase” at the bottom output.
Nulling a Mach-Zehnder output

Adjusting \( \theta \)
sets the “split ratio” of the MZI
that is, how the power from one input would be split between the outputs

Interestingly, for 50:50 beamsplitters adjusting \( \theta \) does \textit{not} change the relative phase with which the two inputs mix at an output
That is controlled \textit{only} by \( \phi \)
Nulling a Mach-Zehnder output

So, since we have already minimized the bottom output power by adjusting $\phi$

if we now adjust $\theta$

we will be able to minimize that power to zero

because the contributions from the two inputs

are already in antiphase at the bottom output
Nulling a Mach-Zehnder output

So, since we have already minimized the bottom output power by adjusting $\phi$
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Nulling a Mach-Zehnder output

So, in 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 $\phi$ second, using $\theta$
Nulling a Mach-Zehnder output

In fact

in making meshes of MZIs
we can use MZI blocks with phase shifters
in any two of these four locations
as long as at least one phase shifter is on an interferometer arm
"Diagonal line" self-aligning coupler

Minimize the power in detector D1 by adjusting the corresponding $\phi$ and then $\theta$, putting all power in the upper output.

Minimize the power in detector D2 by adjusting the corresponding $\phi$ and then $\theta$ putting all power in the upper output.
“Diagonal line” self-aligning coupler

Minimize the power in detector D3 by adjusting the corresponding $\phi$ and then $\theta$ putting all power in the upper output.
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

Binary tree self-aligning coupler

A “binary tree” also supports self-alignment

It uses same number of MZIs in each path

and is the “shortest” possible self-aligning coupler mesh

Each “column” of MZIs can be optimized in parallel

allowing faster self-configuration

Separating multiple orthogonal beams

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 free-space modes

9x2 diagonal line mesh separates two orthogonal free-space input modes automatically by self-configuration


Separating multiple orthogonal beams

Adding more rows and self-alignments separates a number of orthogonal beams equal to the number of beam “segments”, here, 4

Note: it is possible to set this up with only detectors at the outputs though then we may need to “tear down” the network to reconfigure it

If we put identifying “tones” on each orthogonal input “beam” and have the corresponding diagonal row of detectors look for that tone, then the mesh can continually adapt to the orthogonal inputs even when they are all present at the same time and even if they change.


Perfect optics from imperfect components

But what if the Mach-Zehnder interferometers are not perfect?

In particular
the split ratio in the beamsplitters may not be 50:50

Without 50:50 split ratio in the beamsplitters
we cannot in general get perfect cancellation at the outputs
limiting the functionality
Perfect optics from imperfect components

However, there is an algorithm for adjusting the split ratios after fabrication based only on maximizing or minimizing power in detectors to set both beamsplitters to 50:50 after initial fabrication.
Perfect optics from imperfect components

Importantly this does not require any calibrated components or balanced detectors to equalize powers.

If we use MZIs themselves as effective variable beamsplitters the fixed, fabricated split ratios can be as bad as 85:15.

Optica 2, 747-750 (2015)
Self-correcting Mach-Zehnder

Using our algorithm to adjust the effective beamsplitter ratios we can improve the rejection ratio from -30 dB to -60 dB. No calibration or calculations are required. This is based only on power minimization or maximization in an output detector.

Analyzing multimode fields

Suppose we have a field with amplitudes in various different modes. How do we analyze that automatically?

There are various ways to separate modes which could give us the relative magnitudes. But how would we get the relative phases?
Analyzing multimode fields

We could interfere with a coherent reference beam and perform some additional calculations. But we may not have such a beam. For example, if we are looking at a remote source or one that is broadband or of limited coherence.
Analyzing multimode fields

Here we show how to do this

without a coherent reference beam

We repurpose our self-aligning beam coupler

which can perform all the relevant interferences

between all the parts of the beam
Analyzing a multimode field automatically

If we shine in the beam and have this mesh network self-align, then from the settings of the phase shifters in the mesh, we can simply deduce all the relative amplitudes and phases of the inputs.

Example optical input

Binary tree self-configuring mesh

Nulling detectors

Output

Mach-Zehnder blocks

Optica 7, 794 (2020)
Generating an arbitrary multimode field

We can also run this network in reverse shining light backwards into the output to controllably generate any desired multimode field backwards on the left.

Optica 7, 794 (2020)
Pre-compensating a beam

Removing the effects of a diffusing mask with a mesh

1. optimize the mesh to maximize intensity in the center of the camera

Pre-compensating a beam

Removing the effects of a diffusing mask with a mesh

1. optimize the mesh to maximize intensity in the center of the camera
2. introduce a diffusing phase mask
3. re-optimize the mesh settings to restore the central maximum

Optical setup machines

Quite generally, we can use a self-aligning beam coupler as an “optical setup machine.” A system that can essentially calibrate itself and can be used in reverse to controllably generate arbitrary multimode fields.
Setting up other forward networks

We can use such an optical setup machine to calibrate and set up other, arbitrary “forward” optical mesh circuits including ones that are not self-configuring, e.g.,

- lattice filters
- rectangular or hexagonal meshes
Setting up other forward networks

The key trick is to imagine running the desired network backwards with imaginary light shone into just one port of an MZI.

The “Reversed Local Light Interference Method” (RELLIM)

Parallel RELLIM (PRELLIM)

We can also parallelize this
Generally a forward-only network can be reorganized into columns
while retaining the same topology
All the nodes in a given column can be set in the same time-step in parallel
reducing configuration time

Universal self-configuring photonics

Universal architectures

e.g., based on singular value decomposition (SVD)
allow any matrix multiplication for arbitrary linear optics, neural networks, classical or quantum processing and can be self-configured and hence offer universal field-programmable linear arrays
General multiple mode converter

The self-aligning input coupler mesh on the left can couple any four orthogonal inputs
each to different single waveguides in the middle
Light in those single waveguides can be converted into any other set of four orthogonal outputs on the right
by the self-aligning output coupler mesh on the right
The amplitude and phase of this conversion can be controlled by the line of modulators in the middle

General multiple mode converter

This kind of universal mode conversion, with such modulation corresponds to being able to implement an arbitrary (and non-unitary) matrix with such a mesh (at least if we do not require gain) so this mesh is fully universal for performing any linear transformation

The mathematical reason why this works is because we can always perform the "singular value decomposition" of a matrix which means a matrix $D$ can always be written in the form $D = V D_{\text{diag}} U^\dagger$

where $U$ and $V$ are "unitary" (lossless) matrices and $D_{\text{diag}}$ is a diagonal matrix
The optical “units” in the mesh implement the singular value decomposition $D = V D_{\text{diag}} U^\dagger$

This is the first proof that any linear optical component is possible and that any linear optical system can be factored into a set of 2-beam interferences.

This can be used in thought experiments for fundamental proofs.

Decomposing optical systems

We can also flip this logic around.

We can always perform the singular value decomposition of an optical component or system.

So any linear optical system can be described as a mode-converter.


These sets of modes turn out to have basic physical significance.

When we think of how a source function $\psi_S$ in a source space gives rise to a received wave $\phi_R$ in a receiving space for free-space communications, or for any scatterer, optical device, or object between the spaces, there is just some linear operator $D$ that relates the two.

So, mathematically, $\phi_R = D\psi_S$.
Because we can perform the singular value decomposition (SVD) of any linear operator $D$

we have what we can call

the **mode-converter basis sets** of functions

a set of orthogonal source functions $|\psi_{Sj}\rangle$

that lead, one by one

to a set of corresponding orthogonal received waves $|\phi_{Rj}\rangle$
In turn, that means that

there is a set of orthogonal channels
for communication through space
or through any linear scatterer or device
which are given by these mode-converter input and output function pairs

These are the unique and best possible choices
Waves, modes, communications and optics

For any linear optical system

- singular value decomposition gives an optimal, orthogonal set of “input” functions that map, one-by-one, to an optimal orthogonal set of “output” functions.

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

Conclusions

Self-configuring photonics enables complex circuits for new optics
The algorithms to calibrate and use these circuits are simple and fast
We are just beginning to understand the many uses of these ideas

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For a copy of these viewgraphs, please e-mail dabm@stanford.edu
Self-configuring optics references for this talk

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Milanizadeh et al., "Manipulating Free-space Optical Beams with a Silicon Photonic Mesh," 2019 IEEE Photonics Society Summer Topical Meeting Series (SUM), Fort Lauderdale, Florida, 8-10 July 2019, Paper WE1.1


For an overview, including all these links, see https://www-miller.stanford.edu/self-configure

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