Sorting out light

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Controlled interference automatically separates overlapping light beams and creates new optical devices.

When light beams become mixed up, can we sort them out again? Some cases are easy. The light from two flashlights on the other side of the room overlaps when it reaches us, but the lens in our eye separates them again as it constructs an image. By turning the flashlights on and off, we could also now communicate two independent, spatial channels of information to separate “detectors” at the back of our eyes.

But light is easily scrambled by anything more complicated than clear air. Imaging through a strong scatterer like biological tissue rapidly becomes impossible. Even in the near-perfect glass fibers of optical communications, the slightest bend can mix light beams.

Mathematically, interference of light waves just involves adding and subtracting numbers – a “linear” process – so we can exploit the matrices of linear algebra. With effort, we could measure the optical system’s matrix *(1)* and then calculate the “inverse” matrix that would mathematically undo the mixing. But, we have not known how to implement such a matrix as a piece of lossless optics. We did not even know if we could make an arbitrary linear optical device. Now, however, different mathematical approaches *(2-6)*, together with modern microfabrication, may offer a solution. The optics may even solve the problem itself, avoiding any calculations *(5, 6)*.

Historically, optical components were simple objects, like lenses and mirrors. Now, the lithography developed for electronics offers more sophisticated possibilities. Silicon photonics *(7)* and other integrated approaches enable highly functional, complex *(8)* waveguide circuits near the top of a plane surface. Subwavelength patterning enables novel, “nanophotonic” structures, including photonic crystals, waveguides and resonators. Expanding beyond regular structures offers an even wider variety *(2-5)*.

We already use lithography to make diffractive optical elements (DOEs); in those, light travels “through” a thin sheet from one side to the other (or possibly reflects off it). Metasurfaces are extending these possibilities *(9)*. By itself, such an approach cannot implement arbitrary linear optics. A fully arbitrary device *(5)* requires that every distinct element or “pixel” in the output light can be formed from an arbitrary combination of every distinct input pixel, not just by transmission or reflection from the same input pixel.

If the light travels inside the sheet, in waveguides or other complex structures, then light from every input element can possibly interfere to form each output. This multiple scattering makes device design hard. Modern robust optimization algorithms allow efficient “blind” global optimization, however. Various compact nanophotonic devices have now been designed *(2-4)*, for example efficiently converting one set of input beams (or “modes”) to another set of output beams *(2, 3)*.

Another planar approach uses meshes of interfering waveguides *(5, 10)* (Figure 1). We program the mesh through fine adjustments of the lengths or “phase shifts” of waveguide links. We have known the mesh settings for one class of matrices (unitary transformations) for some time. Now, we know an extended form of mesh can implement any matrix, finally proving that any linear optical component is possible in principle *(5)*.

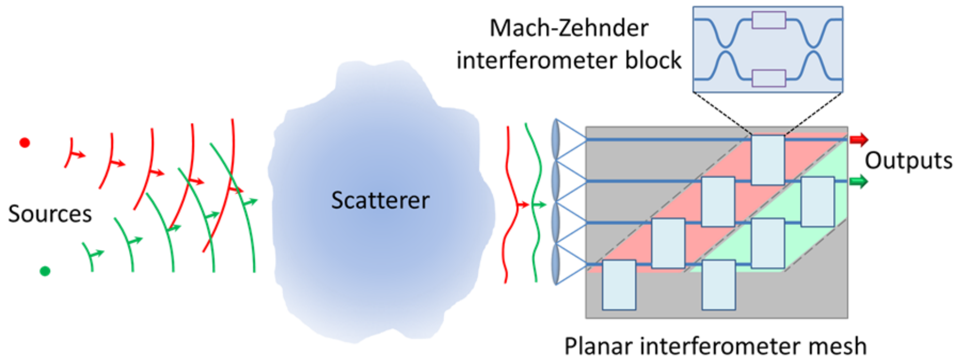

Fig. 1. Light from two sources is mixed and distorted by the scatterer but sorted out by the mesh. The scattered light is focused into waveguides in the interferometer mesh. Progressively adjusting the interferometers in the "red" row to maximize the "red" output separates the "red" power to the upper output. A similar algorithm on the "green" row then separates the "green" power to the lower output. Though shown as "red" and "green", the sources can be the same color or wavelength.

A key to this proof is that we can always perform a singular value decomposition (SVD) of such a matrix *(5)*. The SVD has a simple physical interpretation: For any linear optical device or scatterer, there is a specific set of input beams or "modes" that couple, one by one, to a specific set of output beams or "modes". These input/output pairs or "communications modes" *(5)* completely describe the device, and give independent optical channels through it. The proof is also the design method, mapping the form of the SVD directly into the optics. This SVD approach has another benefit – it allows a progressive, even self-configuring, algorithm (5). We can progressively "train" an extended version of the simple device in Figure 1, using the communications modes themselves, with no calculations

There are still many challenges. We are only at the beginning in fabricating actual optical structures and devices based on the optimization or self-configuring algorithms. The complexity of optical systems we can tackle this way will be limited – imaging even a moderate number of pixels through a strong scatterer remains very challenging. Not all the problems of using multiple mode fibers for communications can easily be solved in the optical domain; time delays between channels in long fibers may necessitate electronic information storage and calculations *(11)*.

Beyond telecommunications or imaging, there are many other potential applications. We need sophisticated optical networks for quantum information processing *(10)*, and for sensor and signal processing generally. Linear optical processors could avoid the power dissipation of electronics. Complex optics could secure signals against decoding *(12)*. Real-time self-configuration could allow automatic beam coupling, optical power combining, tracking of moving sources, and alignment or stabilization of complex optical systems *(5)*. Extensions of these approaches could find the best channels through an optical system *(6)*. This combination of micro- and nano-fabrication, planar optical technologies, advanced robust optimization algorithms, and new self-configuring networks may both generate the new optical results we want and eliminate the ones we would rather avoid.

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Acknowledgments: This work was supported by a Multidisciplinary University Research Initiative grant (Air Force Office of Scientific Research, FA9550-10-1-0264)