Arbitrary Optical Transformations Without Calculations

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Abstract: We show how to perform any linear transformation on a coherent light field, without fundamental efficiency limits, trained, adaptive approach based on singular value decomposition mathematics and suitable for integrated optics implementations in simple cases.
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We are used in optics to performing many useful operations, such as imaging, with optical elements like lenses and mirrors. We can extend to more arbitrary operations using diffractive optical elements or planar holograms, and volume holography offers a broader range of possibilities. But it has not apparently been clear whether we could perform truly arbitrary efficient transformations. The recent need to make mode demultiplexers for possible space-division multiplexing in optical fiber communications highlights this difficulty (see references in [1]). Solutions exist for specific high-symmetry mode forms; but it has not been clear if it is even possible in general to separate multiple, orthogonal overlapping modes without splitting loss. Recently, however, we showed that there is at least one way straightforward and progressive way of designing any such component [1,2] and, by extension, any linear optical component [2]. Furthermore, we can to design it without any calculations or iterations, based only on local single-parameter feedback loops [1,2]. This feedback approach also offers the possibility of complex self-stabilizing optical systems without detailed component calibration.

First we note that any linear optical component can be written as a mode converter [3]; there is a set of orthogonal input waves (or modes) that convert, one by one, to a set of orthogonal output waves (or modes) with given "coupling" strengths. This is a complete description of the linear device; this description always exists because we can always perform the singular value decomposition of the linear operator representing the device. The sets of orthogonal input and output modes emerge from that decomposition, with the singular values giving the coupling strengths. If we choose a minimum coupling strength of interest, the optical problem viewed in this way always becomes one of finite dimensions. (In fact, this "communications mode" approach [3,4] is a rigorous generalization of the idea of diffraction limits, leading to the correct counting of the number of "diffraction-limited" channels.) Based on this finite dimensionality, we can quantify the complexity we need in an optical device [5].

Building on this view of a linear optical device as a mode converter, we recently showed how to build arbitrary mode converter of a given dimensionality [1,2]. One implementation uses a "matrix" of controllable beamsplitters and phase shifters, or equivalently, of Mach-Zehnder (MZ) interferometers [1,2]. We then "train" the device with the desired input and output modes. With a given mode shining into the device, we sequentially adjust the phase shifters and beamsplitters to null out powers on detectors, "recognizing" that mode by channeling all the power to one output.

The simplest device is a self-aligning beam coupler [1] that will take any given coherent beam (of low enough complexity) and automatically align it into a given output beam, such as a single mode fiber. This coupling can be 100% efficient (in principle) regardless of the form of the input beam (provided it is not too complicated for the dimensionality of the optical system). Such a device is interesting in itself, and could have uses from the obvious one of coupling arbitrary and/or varying beams into single mode fibers to different applications such as compensating for blur in a telescope to focus into a single mode spectrometer. (Devices such as photonic lanterns could be interesting "front ends" for this device.)

In this approach, we presume it is a good enough approximation to divide the beam into enough [5] "patches", each approximately uniform in intensity and phase. Fig. 1 shows an example and an extension [6] of the self-aligning beam coupler for the case of an input beam sampled in four segments using grating couplers into single mode guides. This device is capable of separating four orthogonal beams. Obviously the performance of the device is limited by this "patch" sampling operation since it is effectively approximating the beam as four uniform segments, and this kind of sampling limitation is intrinsic to this approach. In principle any sampling loss decreases with increasing numbers of segments, though the device itself becomes proportionately more complicated.

Then with a set of controllable phase shifters and reflectors (see video [1]]), or more practically, a set of MZ waveguide interferometers as in Fig. 1, we couple all the power from the different patches to the single output. In Fig. 1, we work along Row 1, from MZ4 to MZ1, progressively adjusting the phase and split ratios of the MZs in a simple power minimization procedure to null out the powers in detectors 3 to 1. This procedure could be accomplished with simple electronic feedback loops from the detectors to the MZ controls.

The second key concept is that a second, orthogonal input beam will be transmitted through the (mostly transparent) detectors 1 to 3, where it can be aligned similarly with Row 2 to the second output, and so on, thus separating multiple overlapping orthogonal beams without splitting loss [1,2]. If we use a second such device, run backwards, we can convert these single modes to any output modes we want, and modulators in-between can set the coupling strengths to give a completely arbitrary spatial linear optical device. Such schemes are well-suited to silicon photonics, for example. Extensions include spatial add-drop multiplexers [7]; fully arbitrary linear optical devices [2], including polarizations; and automatically finding all the best orthogonal channels through any reciprocal linear optical system [8]. With the addition of circulators [2], the approach can also perform arbitrary non-reciprocal linear transformations. In principle, with the incorporation of frequency shifters [2] it could even perform completely arbitrary linear transformations, including linear operations in frequency space, though the practical implementation of such frequency shifters remains extremely challenging.

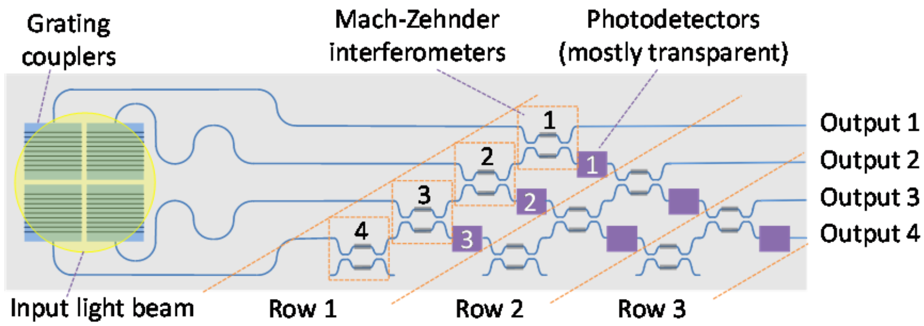

Fig. 1. Schematic of a self-aligning mode coupler and splitter [6].

Note that this device as fully implemented allows the completely separate choice of how each desired optical input mode is converted to a desired output mode. This full flexibility is unlike the behavior of conventional optical components like a lens, for example. We design a lens to take a plane wave and focus it to a specific spot. If we shine a plane wave at a different angle on a lens, the lens will also focus it, to a different spot. Note, though, with the lens that we have essentially no choice as to what happens for this different input; with our scheme here we have free choice of the orthogonal output for a second orthogonal input. A device with this capability is a universal linear device of a given dimensionality. Note this means that we can implement any linear transform between inputs and outputs, a capability we have not previously had available. Note too that this device can be designed entirely by training with the desired orthogonal inputs and outputs, with no calculations. This both proves that arbitrary linear transformations are possible in optics and gives us at least one way in which to implement them.

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