Designing Arbitrary Linear Optical Components Without Calculations

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Abstract: We show any linear optical function on a coherent light beam, such as arbitrary spatial mode coupling and conversion, can be progressively and adaptively designed in a feedback-controlled dynamically self-configuring and self-stabilizing integrated optics approach.
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Historically, we have had many ways of designing and building optical components and configuring complex integrated optics circuits and structures. But recent problems such as spatial mode multiplexing and demultiplexing for communications have emphasized that we have not had a simple approach to the design of arbitrary optical components; indeed, we have not historically known even whether linear optical components that do not otherwise violate basic laws of physics are generally even possible. Recent approaches based on blind, iterative, arbitrary design of nanophotonic structures are promising for the possibility of making arbitrary mode converters or demultiplexers [1-4], though these design approaches require time-consuming global optimization algorithms; but such specific successes do not prove whether it is possible even in principle to separate out arbitrary overlapping orthogonal light beams or modes without fundamental splitting loss. Furthermore, though such approaches offer remarkably compact components with interesting functions, they do not address the issue of how we might make complex functionalities that can adapt in real time, such as spatial mode demultiplexing that can compensate for changes in spatial mode coupling in a fiber. And, as we think about more complex circuits and functions, it is not clear that we have an approach to calibrate and stabilize sophisticated interferometric circuits that we might need for such functions. Recently, we devised an approach that addresses all of these issues [5-10].

(i) It gives a progressive and non-iterative way of designing an arbitrary linear optical component [6,7]; this is therefore also a constructive proof that any linear optical component is possible, including, for example, devices that could separate multiple overlapping orthogonal beams without fundamental splitting loss.
(ii) It offers a practical way of designing and constructing arbitrary linear optical devices [6,7], at least for beams of low to moderate complexity [8].
(iii) The method, which can be implemented directly in analog optical hardware based on simple local feedback loops [6,7,9,10], can be completely self-aligning and self-configuring based on training with the desired input and output beams, and so can adapt, effectively redesigning itself in real time.
(iv) Because of its ability to adapt in real time if we keep training it, it is a self-stabilizing optical system, even though it is interferometric and can be quite complex.

A simple example device based on this approach – a self-aligning beam coupler – is shown in Fig. 1 [6]. Here, the input beam is divided into 9 segments. (The number of segments required in practice will depend on the complexity of the beam [8].) Each segment is grating-coupled into a single mode waveguide, all hypothetically implemented in a technology like silicon photonics. The device has a chain of Mach-Zehnder interferometers (MZIs), with photodetectors on the “drop” ports. We devised a simple algorithm in which we progress along this chain, from left to right, adjusting the phase delays in the arms of the MZIs in a specific sequence to minimize the power in the detectors, one after the other. Once this alignment is complete, the power into all the detectors is nulled out, and all the input power appears at the one remaining waveguide on the right. This scheme therefore ideally couples all the power from the input beam into a single-mode guide, regardless of the specific phase and amplitude in each of the 9 segments. This whole progressive process could be simply automated, requiring only single-parameter feedback loops to minimize the detected powers, thereby giving a self-aligning beam coupler.

This idea can be extended to separate multiple overlapping beams [6,7]. The key point is that if, after aligning the device of Fig. 1 with one particular beam, we were then to shine a second, orthogonal beam on the device instead, none of the power in that second beam would be coupled to the output waveguide; that second beam would all now go into the photodetectors. If we arrange to make the photodetectors mostly transparent, then we can pass the second beam through them to a second row of MZI’s that can then align to that second beam. The process can be further extended. Fig. 2 shows the waveguide and MZI portions of a device that can not only separate four orthogonal beams to separate waveguides in the middle, but can also then transform those into any desired four output beams [7]. The additional MZIs in the middle allow modulation on these four channels through the device. This structure constitutes an arbitrary linear optical device [5] for a “four segment” approximation.

The device in Fig. 2 can be trained with input and output beams to implement any desired linear transformation [5-7]. If the training beams are "keyed" in some way, such as with small amplitude modulations, and the detectors only look for such keyed signals, the alignment can be carried out continuously in the background; this gives a feedback-controlled dynamically self-configuring and self-stabilizing integrated optical system, requiring only simple local feedback loops that could be easily implemented electronically.

Other extensions of this approach allow (i) spatial reconfigurable add-drop filtering to extract specific spatial modes while leaving the other modes unchanged [9], and (ii) systems that can automatically find all the orthogonal channels through a linear optical system [10], such as a multimode fiber with mode coupling.

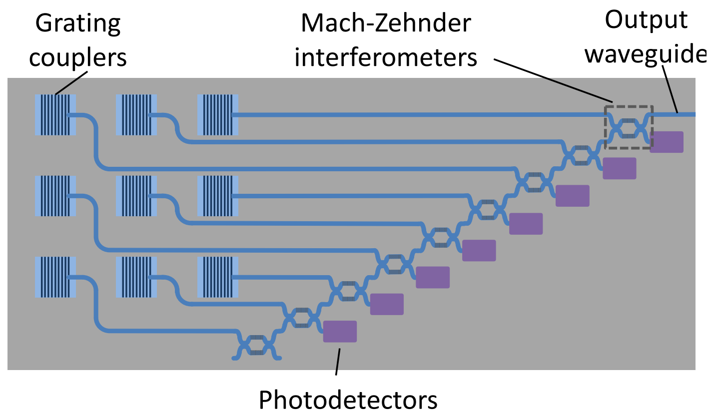

Fig. 1 Figurative top-view schematic of a self-aligning beam coupler. The input light beam shines onto the array of grating couplers, optionally through a lenslet array (not shown), and is coupled into the output waveguide, regardless of the precise form of the input beam [6].

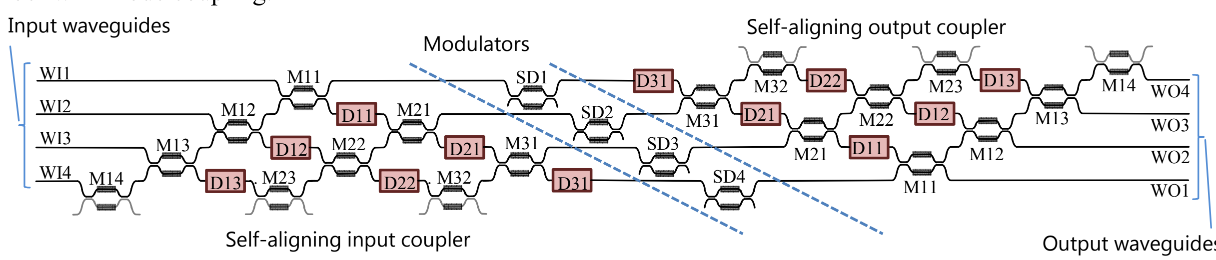

Fig. 2. Waveguides, MZIs, detectors and additional modulators for an arbitrary "four segment" linear optical device [7].

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References

[1] Y. Jiao, S. H. Fan, and D. A. B. Miller, "Demonstration of Systematic Photonic Crystal Device Design and Optimization By Low Rank Adjustments: an Extremely Compact Mode Separator," Opt. Lett. **30**, 141-143 (2005). http://www.opticsinfobase.org/ol/abstract.cfm?URI=ol-30-2-141

[2] V. Liu, D. A. B. Miller, and S. H. Fan, "Highly Tailored Computational Electromagnetics Methods for Nanophotonic Design and Discovery," Proc. IEEE **101**, 484 – 493 (2013). DOI: 10.1109/JPROC.2012.2207649

[3] J. Lu and J. Vučković, "Nanophotonic computational design," Opt. Express **21**, 13351-13367 (2013). http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-11-13351

[4] P. Wahl, T. Tanemura, N. Vermeulen, J. Van Erps, D. A. B. Miller, and H. Thienpont, "Design of large scale plasmonic nanoslit arrays for arbitrary mode conversion and demultiplexing," Opt. Express **22**, 646-660 (2014) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-22-1-646

[5] D. A. B. Miller, "All linear optical devices are mode converters," Opt. Express **20**, 23985-23993 (2012) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-20-21-23985

[6] D. A. B. Miller, "Self-aligning universal beam coupler," Opt. Express **21**, 6360-6370 (2013). http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-5-6360

[7 D. A. B. Miller, "Self-configuring universal linear optical component," Photon. Res. **1**, 1-15 (2013). http://www.opticsinfobase.org/prj/abstract.cfm?URI=prj-1-1-1

[8] D. A. B. Miller, "How complicated must an optical component be?" J. Opt. Soc. Am. A **30**, 238-251 (2013) http://www.opticsinfobase.org/josaa/abstract.cfm?URI=josaa-30-2-238

[9] D. A. B. Miller, "Reconfigurable add-drop multiplexer for spatial modes," Opt. Express **21**, 20220-20229 (2013) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-17-20220

[10] D. A. B. Miller, "Establishing optimal wave communication channels automatically," J. Lightwave Technol. **31**, 3987 – 3994 (2013) DOI: 10.1109/JLT.2013.2278809 http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6581883