Self-configuring silicon photonics

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Abstract. A combination of complex meshes of interferometers with photodetectors and simple feedback loops allows sophisticated photonic systems to configure and stabilize themselves without calibration, and they can be directly, progressively and adaptively trained to perform arbitrary linear functions. Such systems are particularly useful for working with multimode light fields. We introduce and explain key architectures and algorithms.

The ability to make complex photonic circuits, for example with silicon photonics, is opening new opportunities in optics. Many interesting circuits are now being proposed and demonstrated for applications in communications, sensing, and information processing (see, e.g., references in [1] for recent literature). Many such circuits are based on complex meshes of interferometric circuits, such as Mach-Zehnder interferometers (MZIs). Such circuits also offer a convenient way to work with multimode optical fields. Such multimode fields themselves have become of increasing interest in recent years, and offer a new way of thinking about optical systems [2]. Historically, a combination of more than one interferometer would pose severe difficulties in setting and stabilizing the resulting interference. Silicon photonics offer a stable physical platform for such complex systems, which helps in such stability, but still the issue of setting such complex circuits and stabilizing them against unavoidable drifts could still be very challenging.

Now, however, with specific architectures and algorithms discovered [1,3–9] and demonstrated [10–12] over the last several years, we have automatic, progressive ways of configuring, calibrating, perfecting and stabilizing such complex systems; these advances open new possibilities for highly functional, complex, stable, and adaptive systems, including self-configuring, self-perfecting and self-stabilizing networks. One important broad class of networks – "forward-only" meshes [1,9] in which, at least during initial setup, the light only flows in one direction, never reflecting or looping back – allows simple progressive algorithms for setup, calibration, and stabilization. Such an approach, with progressive configuration based on simple, local feedback loops between mesh phase shifters and detected output powers, constitutes the self-configuring aspect of such meshes.

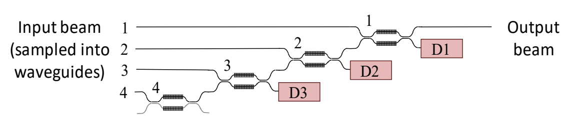

Fig. 1 "Diagonal line" self-aligning beam coupler, with four input waveguides, 4 waveguide Mach-Zehnder interferometers (MZIs), and 3 detectors (D1 to D3) [3].

The underlying idea of such progressive configuration can be understood from a simple example case [3] (Fig. 1). Here we presume that we have four (mutually coherent) optical signals in four input waveguides; for example, these might be from four grating couplers collecting power in segments from a beam, or as four waveguides splitting up the power from some other 4-mode guide. Here we want to couple all of this power into just one output guide or beam, without any calculations or calibration of this simple "diagonal line" mesh of four Mach-Zehnder interferometers (MZIs). To do this, we progressively null out the power in the "drop ports" of MZIs 3, 2, and 1, where

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we have put detectors D3, D2, and D1, which can be accomplished by a sequence of adjustments of the two phase shifters in a given MZI.

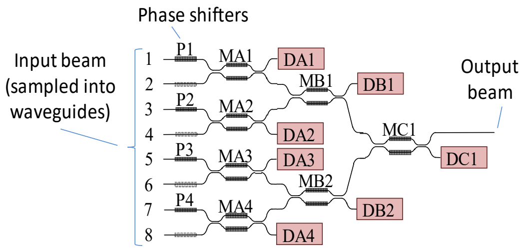

Fig. 2 “Binary tree” self-aligning beam coupler,with columns of MZIs and corresponding detectors DA1 to DC1 [3].

Fig. 2 shows an alternative “binary tree” architecture [1,3]. In this case, the MZIs in a given column can all be set at the same time. This architecture gives the shortest “path” – the smallest number of MZIs in sequence – for a given self-aligning coupling.

Such self-configuring layers can be cascaded to form larger networks that can also be configured automatically and progressively. Including mostly-transparent detectors for the feedback loops allows particularly convenient self-configuring systems [4,12]. Such cascading can be extended to allow any linear operation at a given frequency between the input and output waveguides in a so-called “singular value decomposition” architecture [4].

Specific ideas and extensions include mode separation [4,6,12], establishing optimum channels in telecommunications [2,5], laser beam power combining [3], self-aligning couplers [3], analyzing the full amplitude and phase of a multimode beam [1], controllably generating arbitrary multimode beams [1], and running “perfect” interferometric networks or “field-programmable linear arrays” with imperfect components [7,11]. Recent analysis [13] also suggests that, even working with small sampled powers for the self-configuring process, entire networks could self-stabilize or self-configure in microseconds or less, opening many real-time applications. This combination of fabrication technology with architectures and algorithms may therefore open a broad range of new applications for integrated photonics.

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