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Dimensionality reduction for efficiency human and computer codesign in integrated photonics

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ABSTRACT

Computer design of photonic integrated chip results usually into more efficient solutions, but the key geometrical features that constitute the core of the design, and explain most of its performance and the logic behind them, are difficult to identify. Taking as example densely packed arrays of waveguides, we explain how the knowledge of the physics governing these systems allows the construction of a new representation basis that has much less degrees of freedom than the direct space representation. The analysis of the results of a subsequent Genetic Algorithm optimization reveals new innovative strategy that mediate the shortcomings of human designing.

Keywords: integrated photonics, coupled waveguides, computer optimization

1. INTRODUCTION

The massive use of integrated photonics devices for classical and quantum computing would require the fabrication of ever more complex systems. Photonic Neural Processors (PNP) can be thought of as a good illustration of the problematic faced by Photonic Integrated Chips (PICs).[1] In these systems light must be routed efficiently through multiple input and output ports, using a minimal footprint on the chip, while ensuring at the same time minimal cross-talk between the different channels. Regarding the design of such PICs, the numerous geometrical parameters of the photonics structures are treated as many possible degrees of freedom (DoFs) that must be optimized. In order to cope with this ever growing complexity of PICs, two main designs routes are usually taken.

The first one consists in decreasing drastically the number of DoFs by handpicking a small set of building blocks, each realizing a specific function (e.g. a 50/50 optical splitter), and then to construct the PICs as an assembly of these individual building blocks.[2] A major advantage of this technique is that each design can then be easily reemployed and adapted to other problems. However, the final design is usually bulky. Moreover the initial selection of the building blocks restricts considerably the parameters space that can be explored, and this can compromise the optimality of the final solution. Indeed if a critical feature is absent from the set of building blocks, it can then at best only be emulated by the combination of several blocks but not used directly, hence resulting in a lower device's performance (larger footprint for a lower net efficiency).

At the opposite side, the second design technique makes intensive use of the techniques recently developed in computer optimization, such as the inverse design that can cope with the optimization of extremely large number of DoFs simultaneously.[3,4] This technique results in the designs with the smallest footprint and usually – if the computation capability can offer full 3D electromagnetic simulations – best performances. The main drawback comes from the impossibility to infer in the final design what the important geometrical features are. Consequently it is impossible to adapt a given design to any other – even slightly – different problem (e.g. change of wavelength). Intellectual property cannot also be claimed as no specific features can be identified.

We propose here an intermediate strategy that aims at reducing the number of DoFs to be optimized without compromising much the capability of the final design. We rely for this on the concept of dimensionality reduction, which we will explain below. We will show in particular that this reduction technique results in subsequent

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optimized solutions that can be clearly understood, hence further adapted to other problems. To illustrate further the capability of such a method, we will also present a practical example consisting in the optimization of a routing function through a 5x5 photonic array (see Fig. 2 (a)).

2. DIMENSIONALITY REDUCTION

In order to understand the concept of the dimensionality reduction, one must consider that each DoF that can be optimized constitutes a dimension. The process of the optimization consists then in finding the minimum of a user-defined metrics in this high dimensional space. In this prospect the first design strategy which consists in selecting a few building blocks can be thought – as represented in Fig. 1 (a) – as finding the nearest building block from the optimal solution; then eventually using other subsequent building blocks to correct the remaining error, if possible. To be efficient, the arbitrary-chosen building blocks must therefore have features as close as possible from the ones required in the final solution. To circumvent this issue, the best strategy would be to thin down the numbers of DoFs by removing 'useless' ones, hence performing a dimensionality reduction. If one looks at the sketch in Fig. 1 (b) where a coupled waveguides systems is represented, one can imagine that some modifications of the waveguides' parameters may have no effects (e.g. deep sub-wavelength modification) or that two DoFs may have opposite effect and cancel each other (e.g. redundancy) . Without loss of any generality, we can then choose a hyper-plan in the parameters space that contains only the useful DoFs, the useless one being orthogonal to the hyper-plane. This projection procedure onto a space with lower dimensionality is called dimensionality reduction. So in a sense, dimensionality reduction is already performed implicitly when one defines minimal mesh-size in an inverse design. Here the point is to show that the reduction of the number of DoFs can be more drastic. The main drawback of the dimensionality reduction is that, in order to be optimal, one must know a priori the physics governing the system to be optimized. The advantage, besides the reduction of the number of DoFs, is that the remaining axes after projection have a clear physical interpretation.

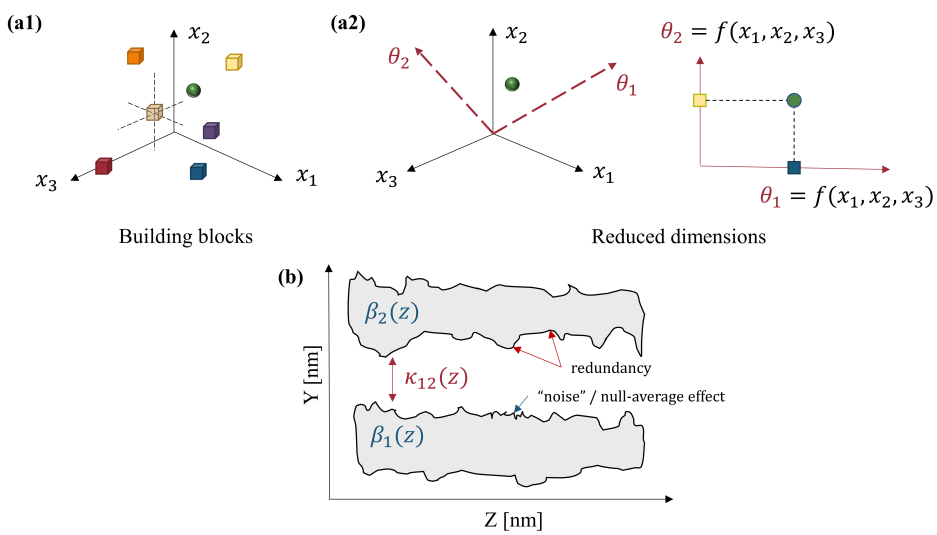

Figure 1. Multidimensional parameter space representation in the case of traditional building-blocks approach (a1) versus reduced dimensions (a2). In the latter case, the final objective (green spehere) can be met by combination of the right coordinates, while for the building-blocks would (here) only result in an approximate solution. (b) Example of the possible result of the optimization of a coupled waveguide system where both waveguides' width and spacing can be changed every nm. In such a design, one can identify features whose actions cancel each other, leading into a more complex design without any performance improvement.

3. OPTIMIZATION OF WAVEGUIDES ARRAYS

We illustrate here in details this concept on the optimization of a dense array of integrated waveguides. The equation governing such a system is very similar to the linear Schrödinger equation used in quantum mechanics.

Such equation can be transformed to make appear two terms: the first one is responsible for the dephasing of the light between two waveguides. The other one is responsible for the coupling, hence the transfer, of the light from one waveguide to another. The details of the underlying theory, that can be qualified as non-adiabatic control, will be detailed in another article. The important point to retain is that there exists a direct mapping between the waveguides parameters (hence the initial large set of DoFs) and the optical function (relative dephasing or transfer of light between the waveguides). The targeted objective is to achieve the prescribed transmission function as illustrated in Figure Fig. 2 (a). Moreover there must be minimal cross-talk between the waveguides so that if the in/out-put ports are extended light would not beat in between the waveguides. To map the effective propagation and coupling parameters $\beta(z), \kappa(z)$ into the geometrical features (waveguide width, interwaveguide gap) we use a semi-experimental formula. Details about the SiN waveguides that are considered are depicted in Fig. 2 (b).

4. HUMAN MADE DESIGN

We present here first a general strategy to design a photonic chip meeting the aforementioned objectives. The cross-talk can be minimized by using waveguides with different effective indices, hence width. Waveguide effective index can then be arranged into a ladder scale (Fig. 2 (c1)). The transfer of light in between waveguides can then be computed by solving an ad-hoc analytical equation, hence creating a direct mapping between the geometrical parameters and the functional (transfer of light). In brief, the solution of the equation results in a sinus-like modulation of the arrays' parameters. By performing sequential transition of light between the neighboring waveguides, the energy flows fulfill then the objectives. Even though the residual light flow is small and the total width of the PIC doesn't exceed 6 μm, the design seems bulky with a total length of 1.5mm. That said this first (un-optimized) example can then serve as comparison with the computer optimization that we will perform next.

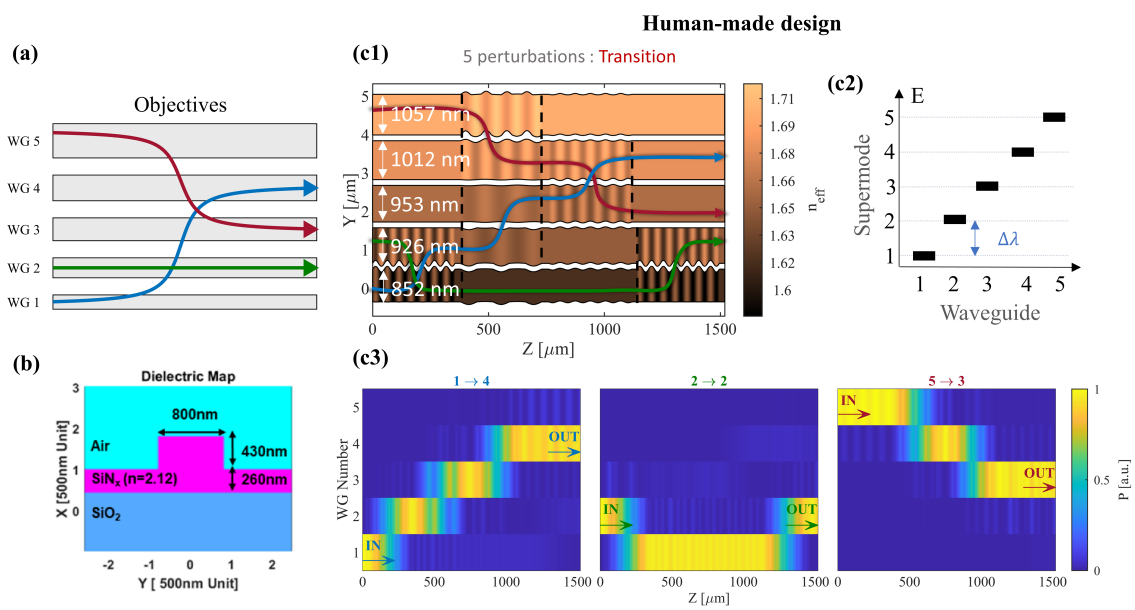

Figure 2. (a) The transitions to be performed on a single PIC. (b) Configuration of each waveguide. Result of human-made design (c1) with the corresponding energy levels structure (c2) and light propagation (c3).

5. COMPUTER MADE DESIGN

We have used a genetic algorithm to generate a computer-optimized solution. The resolution for the design is chosen to be 1 μm so the full problem involves 13500 DoFs. Benefiting from the reduced dimensionality, the PIC's design can be reduced to just 34 parameters. Therefore the optimization was completed within 5 hours on

a regular laptop (Intel I5-7300HQ 2.50 GHz, population size - 300, number of epochs - 100). Score function was represented as a weighted sum of different constraints related to each objectives of the design: Correct routing of the light; Lower cross-talk; and minimal size.

The computer started from a randomized initial guess, so that this is a true computer design (and not a simple optimization of a prior existing solution). The resulted design is displayed in Fig. 3 (a1). Looking at the output gene's structure that directly expresses the computer's intention, we can conclude on the design features without having to interpret the geometrical features. As in the human-made solution, the waveguides are isolated at first and then brought into interaction by the super-modes coupling. The supemodes' energy levels form here an 'alternate ladder', that allows to use each intermediate waveguide as an isolation shield and as a transmission channel, simultaneously. This efficient strategy can result in dense array of waveguides with much greater density. For instance, the waveguide 2 , which has a different width from the two outer waveguides, prevents light leaks without self-elimination from the light routing (compare transitions $1 \rightarrow 4$ and $2 \rightarrow 2$ in Fig. 3 (a2)). Note that the computer has found a solution by using only 3 elementary operations (instead of 5 for the human design) to complete the objectives. Two of them are combined to create an enhanced functionality and responsible for light routing. The third perturbation dephases the light, hence diminishes a residual cross-talk. The modulations' lengths do not exceed 500 μm hence the active part of the device which would require more careful fabrication is now three times shorter than for the human design.

When looking back at the combination of the 2 elementary operations, we see that it exhibits a new feature that is not strictly a dephasing: such a feat could not have been achieved by using individual building blocks. Indeed the computer was able to find an adiabatic elimination[5] (AE) and to combine it with the non-adiabatic transition (namely transition between dissimilar waveguides). Unlike in the general AE approach with two degenerate levels and one upper state (hence, the middle waveguide is different from the two equal outer ones), we have a small energy offset in between these levels as depicted in Fig. 3 (b). Therefore when this energy gap is matched by the transition operation, and the light is routed without energy accumulation in the middle waveguide. Hence it hops directly from the first to the third waveguide.

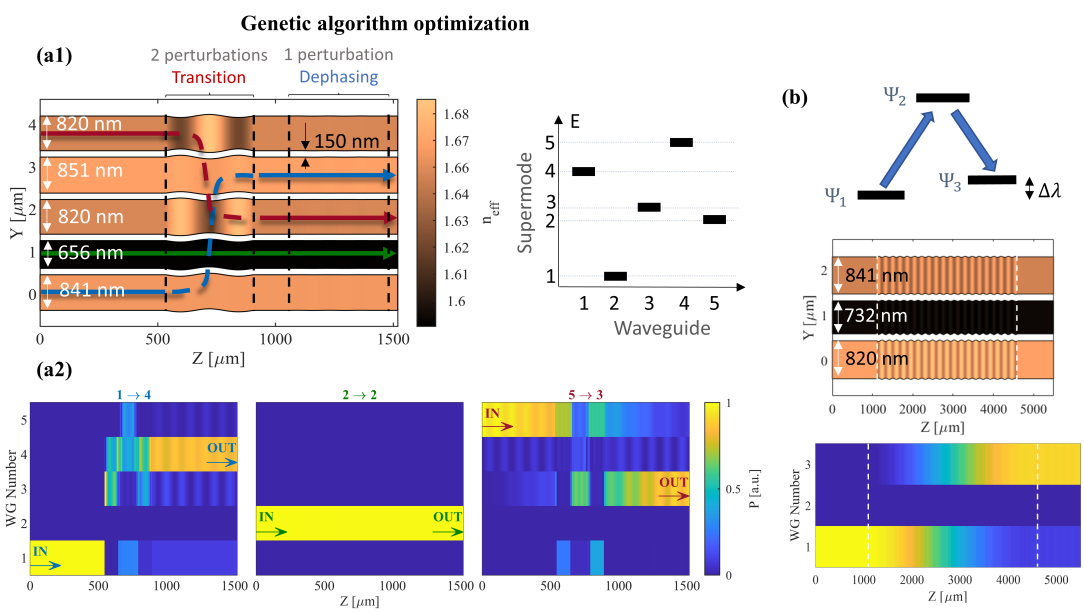

Figure 3. Results of the computer optimization : design and the energy ladder (a1), and the respective light transitions (a2). (b) Combination of adiabatic elimination and non-adiabatic transition.

6. CONCLUSION

We demonstrated that dimensionality reduction allows reducing greatly the apparent complexity of a problem so that it can be solved/optimized easily by a standard computer using standard optimization techniques (here the Genetic Algorithm). Moreover the remaining dimensions (or DoFs) have then a clear physical interpretation so that design strategy can be easily identified. The given choice of projector has allowed us to design a complex light switch in an array of densely packed waveguides. We believe that this approach can be extended to other problems and optimization problems.

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