Optimization of Nanophotonic Structures by Using Genetic Algorithms and Evolutionary Strategies

Xudong Cui and Daniel Erni

General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, Campus Duisburg, D-47048, Duisburg, Germany

We developed several global optimizers based on genetic algorithms and evolutionary strategies, which allow a deeper understanding and a better design of the underlying nanophotonic structures. Design examples are provided such as photonic crystal based waveguides, filters, and plasmonic nanoshell structures for enhanced scattering and absorption applications. Our studies show that the proposed optimization schemes are well suited for numerical structural optimization of nanophotonic components especially when conventional design rules fail or, moreover, when there is not much prior design knowledge available.

The realm of nanophotonics can provide high-speed, large bandwidth and ultrasmall optical / opto-electronic components. In this talk, we present the design and optimization of nanophotonic structures by means of two global bio-inspired search heuristics, namely genetic algorithms and evolutionary strategies [1]. The application of evolutionary optimization algorithms in computational optics has already proven successful in various fields, namely integrated optics, multi-section laser design, optical data communications, and optical sensors [2]. Here, advanced nanophotonic components, such as photonic crystal waveguides, photonic crystal filters and nanoshell structures are optimized respectively for waveguiding, filtering and for the enhancement of light scattering.

In particular we designed: (1) a tight hybrid waveguide bend which combines a conventional dielectric waveguide with a photonic crystal [3]; (2) a compact filter structure formed by inserting a photonic crystal into a straight waveguide section [4]; and (3) nanoshell structures for photothermal applications with optimized scattering and absorption cross sections.

Our studies reveal that genetic algorithms and evolutionary strategies are well-suited for efficient nanophotonic device design and optimization. It’s worth mentioning that molding sub-wavelength light fields in nano devices is hardly tractable without using numerical structural optimization, because conventional design rules either fail or there is not much prior design knowledge available as is the case in the structures investigated in this talk.

[1] J. H. Holland, *Adaption in Natural and Artificial Systems*, MIT Press, New York (1968).
[2] D. Erni et al, *ACES J.* **15**(2), 43 (2000).
[3] X. Cui et al, *Opt. Express* **14**, 4351 (2006).
[4] X. Cui et al, *J. Opt. Soc. Am. A* **24**, 1761 (2007).

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1. Genetic Algorithms and Evolutionary Strategies

The main advantage of stochastic optimizers such as Genetic Algorithms (GAs) and Evolutionary Strategies (ESs) is that such optimizers are not trapped in local optima and need not to be started with a sufficiently good initial guess of the solution [1]. This is advantageous for optimization. Although GAs are currently widely used for the optimization in high-dimensional real-valued parameter spaces, these algorithms are not really efficient when difficult engineering problems are solved, where the numerical evaluation of a single model is time consuming. In such cases one would like to find maybe not the global optimum but a sufficiently good local optimum with a very small number of model evaluations of order 100 or 1000. Since the population size of standard GAs is of the same order, it is evident that such optimizers are not much better than random search, which is certainly not good enough. Therefore, one either must use micro-GAs with a typical population of only 5 individuals or ESs with small populations, for example, (1+6) ESs or (1,6) ESs. For difficult cases that require hundreds of model evaluations, the population size, GAs and ESs have several additional parameters that influence their performance. The optimization of these parameters is extremely time consuming and often poses severe problems for the user. To overcome these problems, we first designed simplified test examples, including photonic crystal based waveguides[2], filters [3], and plasmonic nanoshellstructure. These test examples were then used to find optimal tuning of the GAs and ESs.

2. Fitness definitions

Fitness definitions are important for any kind of optimization. As an example, here we first define the goal of the optimization by defining a fitness function as illustrated in Fig.1 for a band pass filter. Note that the definition of the fitness function is not unique. Often one defines several barriers for either low or high transmission. For each barrier area one then evaluates the error of the transmission function *T(f)*. Then, the fitness may be defined as:

$$Fit(p_1, p_2, \ldots, p_N)=1/\sum_{n=1}^{N_b} E_n$$

where N_b is the number of barriers and E_n the error over the area of the n-*th* barrier. It is usually resonable to use weighted error sums with weights w_n when one of the barriers spans only a small frequency range,i.e., in the design of narrow band filters. Generally, the fitness function depends on the model parameters p_m and often has thousand of different local optima. Most of the local optima deliver impractical solutions. Stochastic optimizers may then be used to select the few promising structures, characterized by high fitness values.

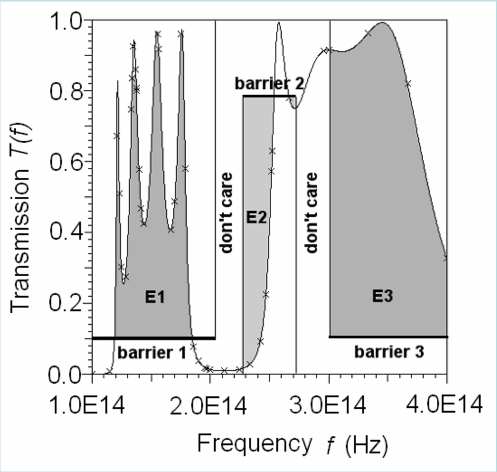

Fig. 1 Fitness function definition for a band pass filter. In the diagram of the frequency dependence of the transmission coefficient *T(f)*, three barriers are defined. *T* is requested to be below barrier 1 and 3 but above barrier 2. Between the barrier areas one has two “don’t care” areas where arbitrary values of *T* are accepted. The gray areas E1, E2, E3 indicate the error integrals in the three barrier areas.

1. D. Quagliarella et al, *Genetic Algorithms in Engineering and Computer Science,* Chichester, John Wiley & Sons, pp. 1-391 (1998).
2. X. Cui et al, *Optics Express*, 13, 6175-6180 (2005).
3. X. Cui et al, *J. Opt. Soc. Am. A* 24, 1761-1766 (2007).

3. Test Examples

3.1 Photonic Crystal Based waveguides

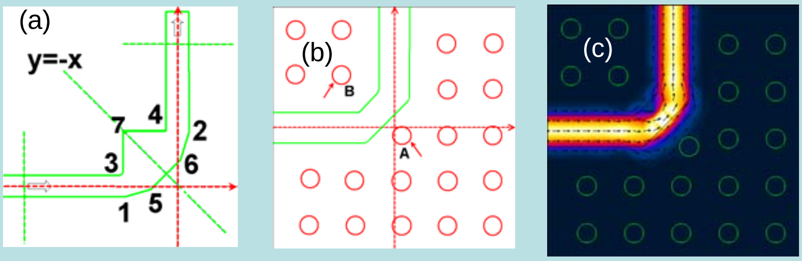

Fig. 2 (a) An optimization scheme for a dielectric waveguide bend. The coordinates of the corners indicated in the figure are moving as *y=-x* during optimization. The width of the waveguide is 400nm with refractive index n=3.24.(b) An optimization scheme for the hybrid structure, where the photonic crystals (lattice constant is 600nm and the diameter of the rod is 120nm) are put on both sides of the bend, A and B marked in the figure indicate the most sensitive rods in such a hybrid structure. (c) Poynting vector of the optimized structure with transmission 99.98% for the dominant mode, see [2] for the detailed parameters.

3.2 Photonic crystal based filters

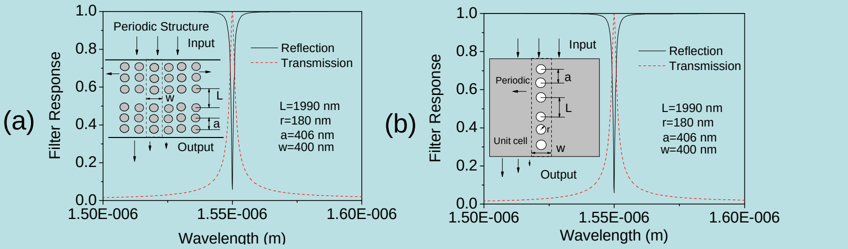

Fig. 3 (a) Photonic crystal slab filter and its response, TE polarization (***H***-field is perpendicular to the page plane), dashed rectangular: periodic unit cell in calculation; (b) Filter response with different layers on both sides of cavity as shown in (a), also see [3].

3.3 Nanoshell structure optimization

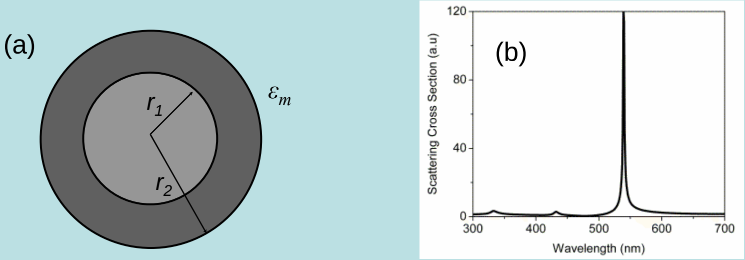

Fig. 4 (a) The nanoshell structure under optimization. The core layer is silica and the radius is r_1, the shell layer is silver and the shell thickness is r_2-r_1, the goal is to maximize the scattering or absorption at certain wavelength based on the geometric parameters and surrounding media; (b) The spectral response for the optimized nanoshell structure.

Xudong.cui@uni-due.de