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Design of Compact Nano-Optical Couplers Involving Dielectric Nanorods

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Abstract

We present optimization and design of nano-optical couplers involving dielectric nanorods. Using tens of elements, optimal array configurations are found to produce alternative responses that can be digitized. For realistic simulations, the couplers are modeled as three-dimensional structures and analyzed via surface integral equations and the multilevel fast multipole algorithm (MLFMA). Initial results are presented demonstrate the feasibility of compact but effective couplers with desired responses.

1 Introduction

Periodic arrangements of dielectric objects, which are commonly known as photonic crystals [1], have been studied for decades and are widely used in many applications in electromagnetics. Engineering these structures for various purposes have also attracted the interest of many researchers [2]–[8]. Numerical solvers have been combined with optimization tools in order to design high-performance arrangements of dielectric elements with desired transmission, reflection, and absorption characteristics [6]–[8].

In this work, our purpose is to design compact nano-optical couplers involving dielectric nanorods. The desired properties are (i) couplers should be compact (several micrometers/wavelengths), (ii) they should be relatively simple (involving tens of rods), and at the same time, (iii) they should provide a variety of desired outputs for given inputs. Specifically, considering a square block and an excitation from one edge, the couplers should be able to provide alternative outputs at the other edges, such as 000, 001, 010, 100, 011, 110, 101, and 111, where 0 and 1 represent block and pass, respectively. For the design of such couplers, we use an optimization environment based on genetic algorithms (GAs) and an efficient full-wave solver, i.e., the multilevel fast multipole algorithm (MLFMA) [10],[11]. Initial results, some of which are presented in this paper, demonstrate the feasibility of compact couplers, as well as challenges and required improvements for their practical usages.

A related work can be found in [9], where couplers involving plasmonic nanoparticles are used to improve the transmission properties of bended nanowire systems without any controllability.

2 Optimization Environment

For the optimization and design of couplers, we consider an implementation involving an integration of GAs and MLFMA. For the examples in this paper, the GA module works on pools of 40 individuals, each representing a candidate solution to the optimization problem. On/off optimization is performed by considering each dielectric rod independently and choosing its existence or absence. For a 10×10 compact coupler involving only 100 rods, this corresponds to $2^{100} \approx 1.27 \times 10^{30}$ different configurations that cannot be scanned one by one. Using GAs, maximum 50 generations are performed, leading to a total of 2000 trials per optimization (neglecting repeating configurations), for satisfactory results.

Each optimization trial is considered as a scattering problem to be solved by using the developed MLFMA implementation. The problems are formulated with the electric-magnetic current combined-field integral equation. Rao-Wilton-Glisson functions defined on triangulated surfaces

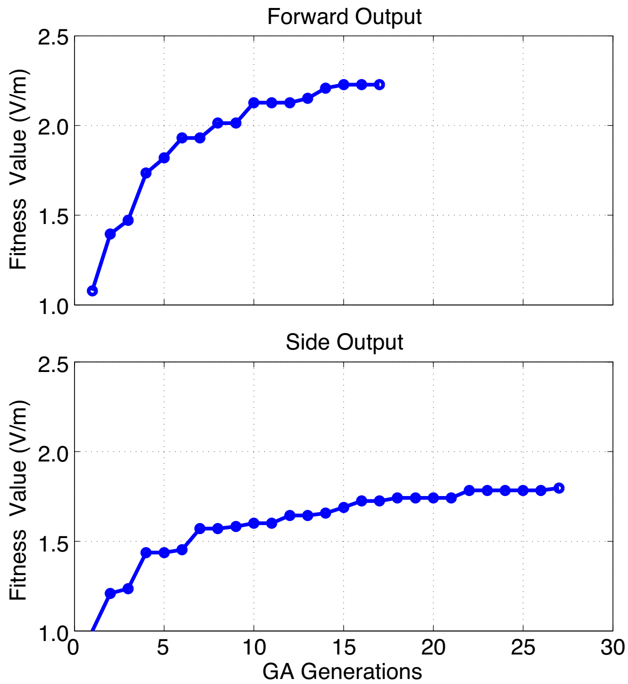

Figure 1. Optimization histories for the design of couplers when excited by a plane wave at 200 THz.

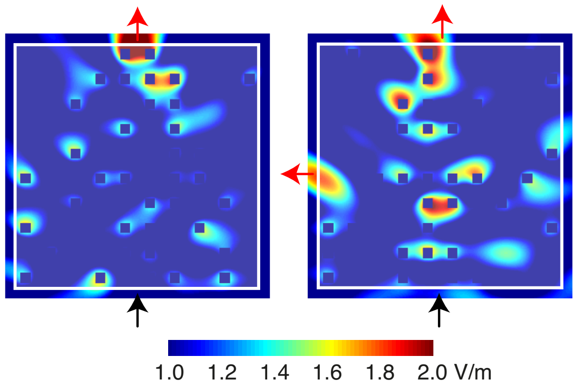

Figure 2. The electric field intensity (V/m) in the vicinity of the designed couplers that can provide forward output (left) and forward+side output (right) when illuminated by a plane wave at 200 THz.

are used for expanding equivalent currents on rod surfaces. Iterative solutions are performed by using the generalized minimal residual (GMRES) method, while the matrix-vector multiplications are accelerated via MLFMA. More information on the MLFMA implementation and the developed optimization environment can be found in [12]–[14].

3 Numerical Examples

As numerical examples, we consider compact couplers involving 10×10 grids of $0.15 \times 0.15 \times 7.5$ μm dielectric rods. The rods are aligned in the z direction (7.5 μm length), while they are arranged periodically with 375 nm center-to-center distances (on the x-y plane). The relative permittivity of the rods is 4.0, while they are assumed to be located in vacuum. The frequency is set to 200 THz.

First, we consider the case when the excitation is a plane wave (1 V/m), which represents a uniform excitation of the coupler (e.g., a wide laser beam). Fig. 1 presents optimization histories (fitness values with respect to GA generations) for two different cases, assuming that the coupler is excited from the bottom edge when it is observed in the x-y plane.

- Forward Output: The electric field intensity is maximized at a single output location on the top edge of the coupler. The fitness value to be maximized is selected as the value of the electric field intensity at the target location.
- Forward+Side Output: The electric field intensity is maximized simultaneously at two locations; one on the top edge and another on the left-hand side of the coupler. In this case, the fitness value to be maximized is selected as the minimum of the electric field intensity values at the output locations.

As depicted in Fig. 1, in the first case, the fitness value can be increased to 2.23 V/m just in 17 generations followed

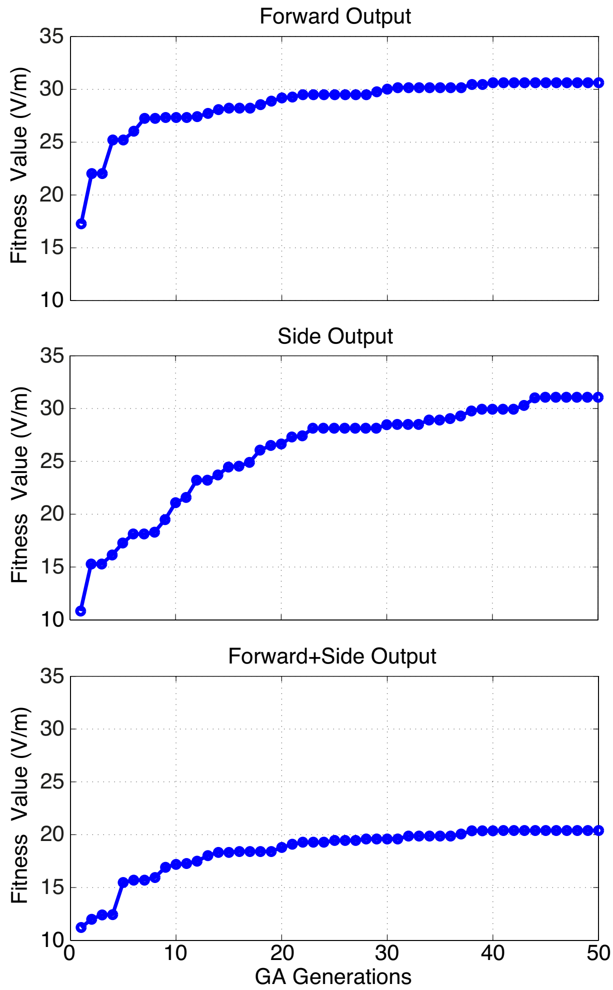

Figure 3. Optimization histories for the design of couplers when excited by a CSB at 200 THz.

by a saturation. In the second case, the fitness value can be increased to 1.8 V/m in 27 generations. Fig. 2 presents the electric-field intensity (V/m) in the vicinity of the designed couplers. The region of couplers is enclosed inside the square box with white lines, while the output locations are shown with red arrows. It can be observed that the desired outputs are successfully obtained.

As a second set of results, we consider a complex-source-point beam (CSB) excitation (that exactly satisfies the Maxwell's equations), which simulates a narrower laser beam. We consider three different optimizations, i.e., forward output, side output, and forward+side output (as defined above). In the forward+side case, the fitness value is again defined as the minimum of two electric field intensity values. Fig. 3 presents the optimization histories for all three cases. Using 50 generations, the fitness value can successfully be increased to 30.64 V/m, 31.07 V/m, and 20.4 V/m, respectively. Fig. 4 depicts the electric field intensity (V/m) at around the couplers, in addition to the intensity of the excitation itself for comparisons. Similar to the plots in Fig. 2, the coupler regions are shown with white-edged boxes. We observe that the couplers operate

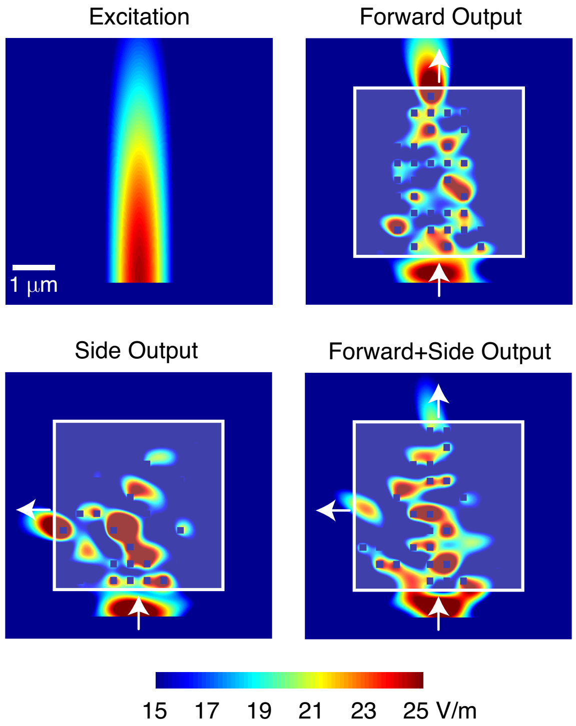

Figure 4. The electric field intensity (V/m) in the vicinity of the designed couplers that can provide forward output (top-right), side output (bottom-left), and forward+side output (bottom-right) when illuminated by a CSB at 200 THz. The electric field intensity of the excitation is also shown (top-left) for comparisons.

successfully by providing the desired outputs.

4 Concluding Remarks

We present the optimization and design of compact nano-optical couplers involving dielectric rods. By using an optimization environment based on an effective combination of GAs and MLFMA, we design various couplers that can provide desired outputs despite their relatively small and simplified geometries. The results demonstrate the feasibility of compact couplers that can be used in photonic integrated circuits.

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