Shape Optimization of Nanophotonic Devices Using the Adjoint Method

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Abstract: We use an adjoint method integrated with a classical Maxwell solver to optimize several nanophotonic devices, providing an adaptable and efficient tool for photonics design.

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1. Introduction and motivations

Shape optimization of photonic components is gaining momentum in many areas of nanophotonics. Both derivative-free and derivative-based optimization methods have been implemented. The former require heuristic methods such as particle swarm optimization or genetic algorithm that require the solution to be calculated a large number of times for pseudo-randomly chosen shapes. Hence, these derivative-free methods only work well when optimizing few variables and when the electromagnetics simulations are quick. Although these methods are already included in many electromagnetic solvers [1], calculating the shape derivatives can provide much faster local optimization. The derivative, which enables the use of efficient algorithms such as gradient descent or quasi-Newton methods, allows for the optimization of electromagnetic problems with high computational costs like nanophotonics.

Unfortunately, calculating shape derivatives often requires the use of dedicated software. Recently, we have shown that it is possible to use classical Maxwell solvers to calculate shape derivatives by using an adjoint method [2], enabling us to optimize a wide variety of problems using already existing electromagnetic simulation tools.

2. The adjoint simulation

An efficient way to calculate the shape derivatives for different electromagnetic design problems is to use the adjoint method. This requires solving an adjoint problem that is closely related to the forward problem (ie calculating the figure of merit). Symmetries in the Maxwell Green's function enable us to use the same solver to perform this calculation. For example, for a mode matching problem, where the figure of Merit is power coupling into a given mode (such as the problem illustrated in figure 1), the adjoint simulation simply consists of propagating the desired output mode backwards into the coupling structure. This can easily be done without needing to program a specific adjoint solver. The computational cost is minor, as finding the shape derivatives in the entire design space requires only one adjoint calculation, which takes the same time as doing the forward simulation.

While we will not derive how the adjoint sources are calculated here, we direct the reader towards [2,3], where the process is described in much greater detail.

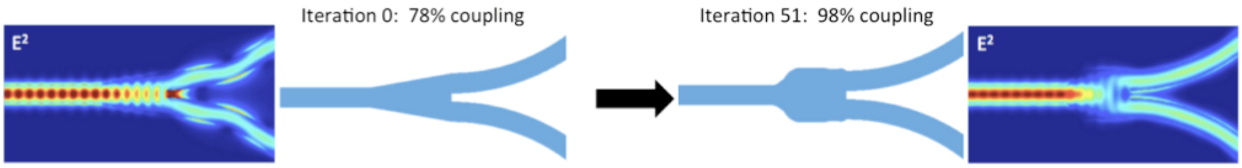

Fig. 1: Top view of the silicon splitter geometry obtained before optimization and after 51 iterations of the Steepest Descent algorithm. The Silicon waveguide is 220nm thick, and the cladding is Silicon dioxide. The figure of merit is coupling into the two separating waveguides.

3. Examples

Once the derivatives with respect to the index of refraction are known, it is possible to run a routine such as gradient descent in order to optimize the performance of the device. In [2] we optimize the efficiency of a Y-splitter in Silicon photonic technology, as summarized in figure 1. Other optimizations [4] performed using this method include an optical antenna for heat assisted magnetic recording [5] (figure 2), absorption in a thin solar cell structure [6] (figure 3), or lithography mask design (figure 4).

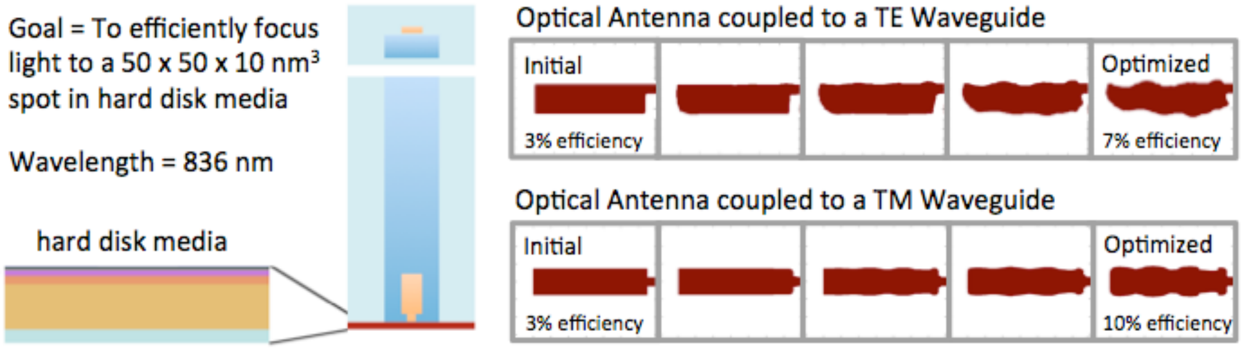

Fig. 2: Optical antenna shapes that are optimized to deliver mWs of energy to a subwavelength spot on a hard disk for Heat-Assisted Magnetic Recording. The optical antenna is a planar film of gold coupled to a TE or TM mode waveguide. A similar system could also be used for spectroscopy, replacing much less efficient NSOM tapered-fiber probe tips. (from [5])

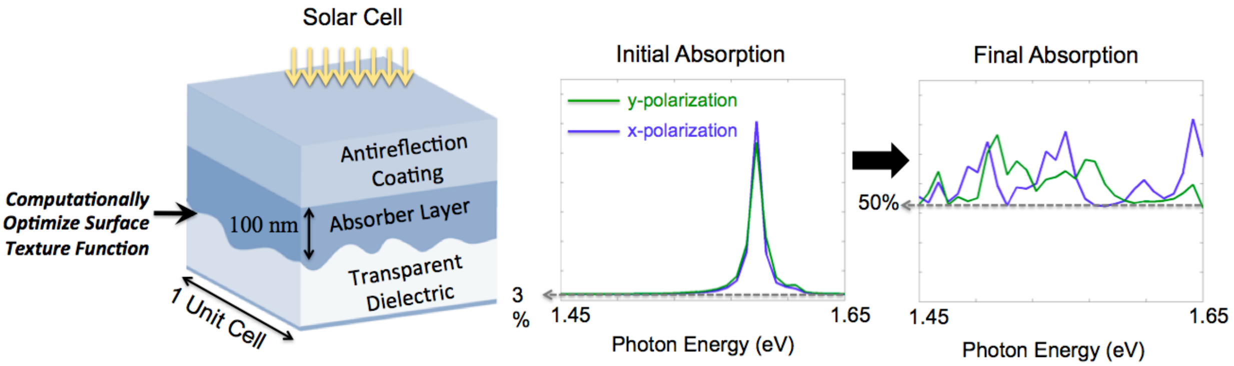

Fig. 3: Schematic view of the solar cell configuration and optimization results (from [6])

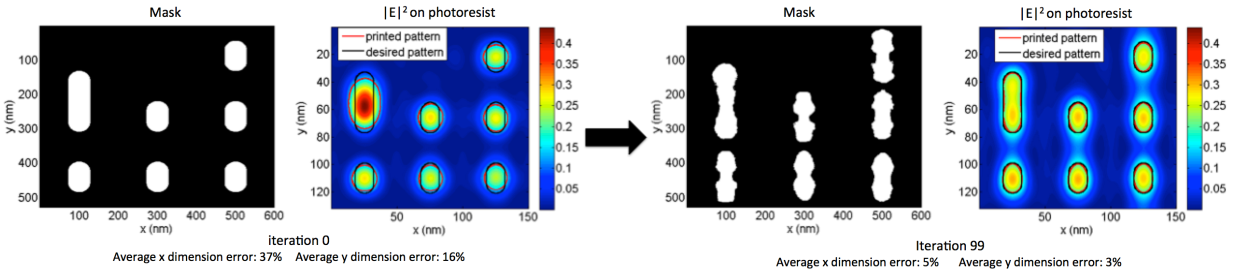

Fig. 4: Above is an example of extreme ultraviolet (EUV) lithography mask optimization using the adjoint method. In the mask patterns shown, white areas are perfectly transmitting, and black areas are perfectly opaque. The wavelength used is 13.5 nm, the numerical aperture fo the system is 0.33 and there is a 4x demagnification between the mask and the wafer. The intensity shown is normalized to clear field. The mask is periodic, with one unit cell shown here

4. Conclusion

We have presented an efficient way of calculating shape derivatives for nanophotonic devices that can be seamlessly integrated with existing Maxwell solvers, and provide an adaptable and efficient tool for a wide range of photonic device optimizations.

5. References

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