

# Inverse Design of Optical Antennas for Sub-Wavelength Energy Delivery

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**Abstract:** We report using Inverse Electromagnetic Design to computationally optimize optical antenna shapes. Optimized antennas deliver 10% of incident power to a  $50 \times 40 \times 10 \text{ nm}^3$  spot in a practical magnetic recording medium for Heat Assisted Magnetic Recording.

**OCIS codes:** (260.3910) Metal optics; (210.3810) Magneto-optic systems; (180.4243) Near-field microscopy

## 1. Introduction

Previous work achieved the focus of optical energy to a 10 nm spot size with gold-coated tapered optical fibers, used in Near-Field Scanning Optical Microscopes. However, tapered fibers are remarkably inefficient, and typical optical transmission to a sub-100 nm spot is on the order of  $10^{-5}$  to  $10^{-7}$ , severely limiting the scan rate to 10  $\mu\text{m/s}$  or less [1]. Recently, interest in this problem has been renewed by the data storage industry toward commercializing Heat Assisted Magnetic Recording (HAMR). This data-recording scheme relies on focusing optical energy to locally heat the area of a single datum, several hundred square nanometers on the hard disk. In order to write data with a scan rate of up to 10 m/s, the optical system must heat the media by 200 K within 1 ns which amounts to  $\sim 1 \text{ mW}$  delivered to a 30 nm spot [2,3]. Hence, for practical diode laser powers, the system must achieve an energy coupling efficiency of at least 5% or  $10^5$  times the transmission of tapered fiber. This also represents  $10^2$  to  $10^4$  times more power than typical electron-beams, which provide 0.1 to 10  $\mu\text{W}$  [4].

Published solutions for HAMR either contain a complex optical system, such as the Planar Solid Immersion Mirror [2,3], or an antenna difficult to manufacture by top-down fabrication, such as the C-Aperture Antenna [5]. Perhaps, a simpler solution for sub-wavelength energy delivery may be a planar antenna excited by a rectangular waveguide, which are simple to fabricate and can butt-couple to a single-mode laser. We used Inverse Electromagnetic Design to computationally optimize shapes of gold planar optical antennas coupled to 830 nm TE and TM waveguide modes. Optimized antennas with a  $50 \times 40 \text{ nm}$  peg delivered 10% of incident power to a 10 nm thick magnetic recording layer in a practical hard disk media stack. This optical system can also be readily applied toward microscopy and lithography to achieve significantly faster scan rates.

## 2. Inverse Electromagnetic Design

For electromagnetics problems, a computational algorithm that is capable of automatically designing optimal geometries of dielectric or metal objects in an optical system is very desirable. Applications include designing antennas to deliver optical energy to sub-wavelength spots, nano-textures for light-trapping in sub-wavelength thick solar cells [6], and couplers between waveguides and integrated optoelectronic devices.

Our Inverse Design method is considered Adjoint-Based Gradient Descent. In our unique implementation, we model dielectric or metallic boundary perturbations as dipole scatterers and use Lorentz reciprocity to efficiently calculate the effects of each dipole scatterer. From this, we can calculate the sensitivity of a Merit Function with respect to every possible perturbation to an object's boundary. This method achieves a non-parametric optimization that requires only 2 Electromagnetic simulations per iteration. In contrast, parametric optimizations do not generate creative or non-intuitive shapes and require more than  $2N$  simulations per iteration, where  $N$  is the number of varied parameters. A detailed derivation of this method and its computational efficiency are beyond the scope of this paper and available elsewhere [7,8]. An illustration of the Inverse Design method is shown in Figure 1. When applied to antennas, the 2 simulations (Forward and Adjoint) are equivalent to far-field illumination and near-field excitation.

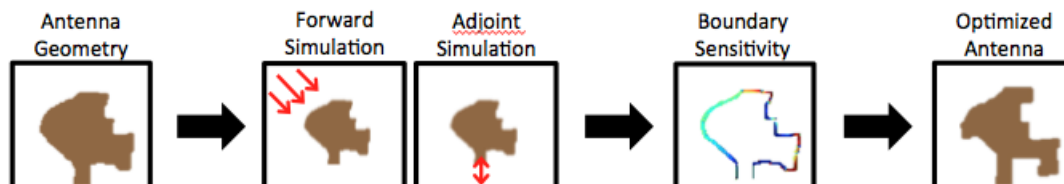


Figure 1: Illustration of the Inverse Electromagnetic Design method. Only two simulations are needed to calculate Boundary Sensitivity, which indicate where the boundary should be pushed outward (red) or inward (blue) to further optimize the shape.

### 3. Application to Heat Assisted Magnetic Recording

We used an FDTD Electromagnetics Solver and our Inverse Design algorithm to investigate and find optimal shapes for planar gold antennas that can couple to the TE and TM rectangular waveguide modes. The major design difference between the TE and TM modes is the requirement of an asymmetric versus symmetric antenna, respectively shown in Figure 2a. We optimized for optical coupling efficiency, defined as energy absorbed in the 10 nm thick storage layer within the hotspot's FWHM divided by the incident power injected into the waveguide. Initial antenna shapes were taken to be  $150 \times 650 \text{ nm}^2$  rectangles of 40 nm thick planar gold. To accurately resolve the quickly changing electromagnetic fields at the interface of the antenna, air-bearing surface and hard disk media as shown in Figure 2b, the smallest Yee cell dimension used was 0.5 nm.

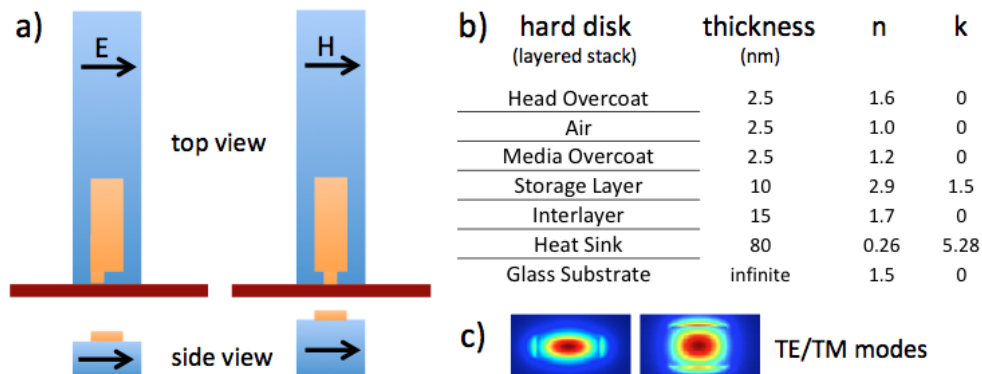


Figure 2: a) Proposed optical system consists of a planar optical antenna (gold) above a TE/TM rectangular waveguide (blue) abutting a hard disk (red). b) Detailed structure of the hard disk media stack and air-bearing surface. c) Electric field intensity of the TE/TM waveguide modes.

Figure 3 shows the successful use of Inverse Design to computationally generate non-intuitive antenna shapes optimized for HAMR. The optimized antennas could not be designed by hand and deliver great energy coupling efficiencies of 7% and 10% for the TE and TM modes, respectively. The  $50 \times 40 \text{ nm}$  antenna peg clearly defines the dimensions of the hotspot inside the 10 nm thick storage layer. These simple waveguide and planar antenna systems can be applied not only to Heat Assisted Magnetic Recording but also to future high-scan-rate Near-Field Microscopy and Lithography.

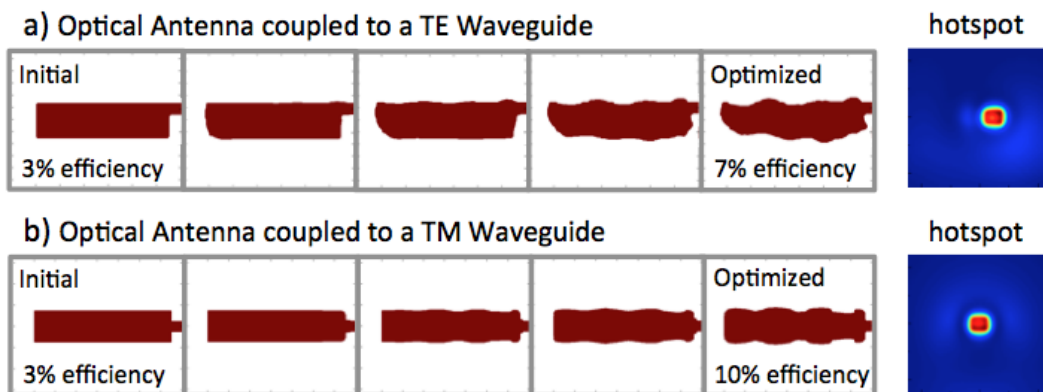


Figure 3: Optimization of optical antennas coupled to the TE and TM waveguide modes (left). Electric field intensity in a  $500 \times 500 \text{ nm}^2$  cross-section in the storage layer of the hard disk, showing a hotspot defined by the antenna peg (right).

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