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Predicting the Optical Response of a Generalized Multilayer Thin Film

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Theoretical Consideration in Near-Field Magneto-Optical Microscopy

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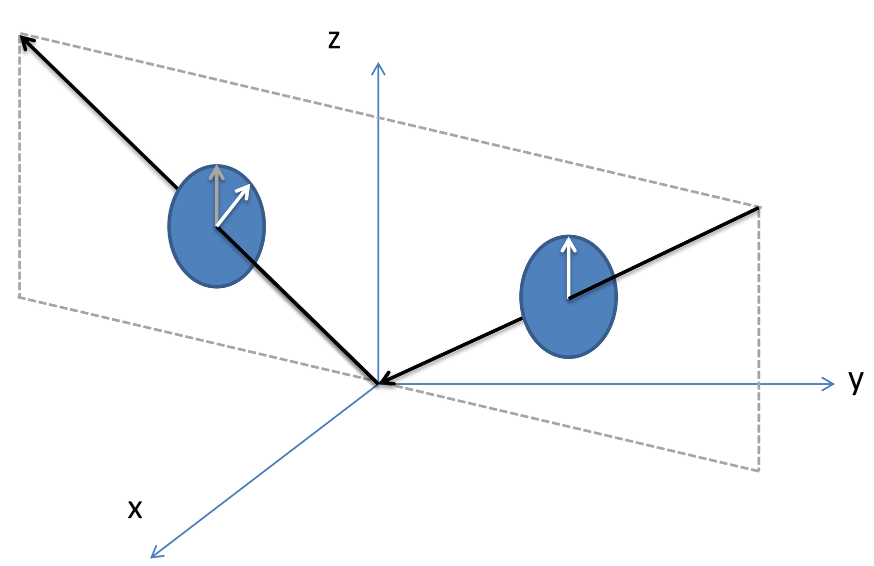
Abstract

The contrast mechanism in Kerr imaging is the apparent angle through which the plane of polarization is rotated upon reflection from a magnetic surface, and this can be calculated for a well characterized surface given the polarization state of the incident light. As in traditional optical microscopy, the spatial resolution is limited by diffraction to roughly half the wavelength of the illumination light. The diffraction limit can be circumvented through the use of near-field scanning optical microscopy, in which the illumination source is an evanescent field at the tip of a tapered optical fiber. The complication in merging these two techniques arises from the complex polarization profile of the evanescent field. This profile can be characterized for a given probe geometry with the use of electromagnetic field modeling software, thereby allowing for subsequent modeling of the polarization profile of the optical response. An algorithm for predicting the optical response to a near-field probe tip from a generalized multilayer thin-film is discussed.

Theory

Magneto Optical Kerr Effect (MOKE)

Light is a wave of electric and magnetic fields. When such a wave reflects from a simple surface, these fields are unaffected. They continue to oscillate in the same direction relative to the propagation of the light. A sample with electric or magnetic properties, however, will actually shift the axis of the electric and magnetic fields (referred to as the polarization of the light).

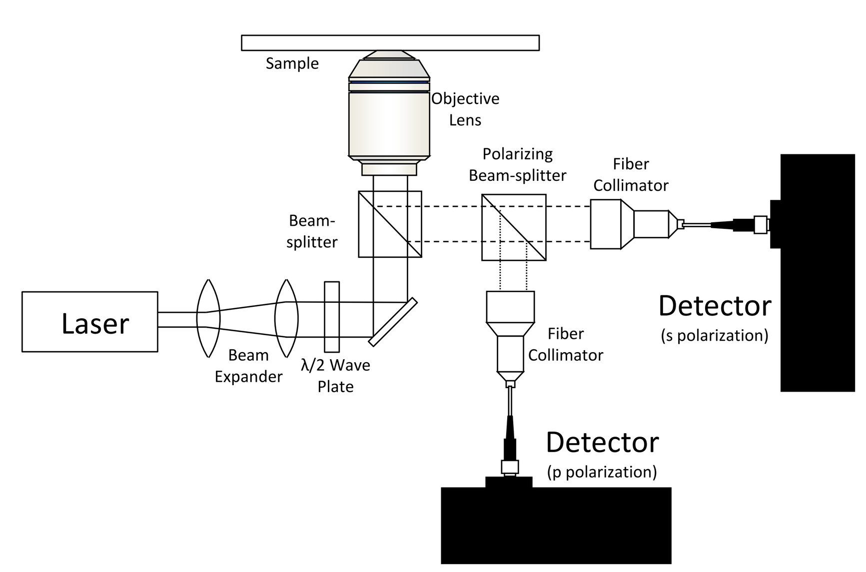


In the illustration (left), the light reflects from a magnetic surface. The direction of the magnetic field is initially straight up. Upon reflection, the field has rotated to its new position (shown by the white arrow).

This phenomenon is known as the Magneto-Optic Kerr Effect, and can be used to image magnetic samples with an optical microscope.

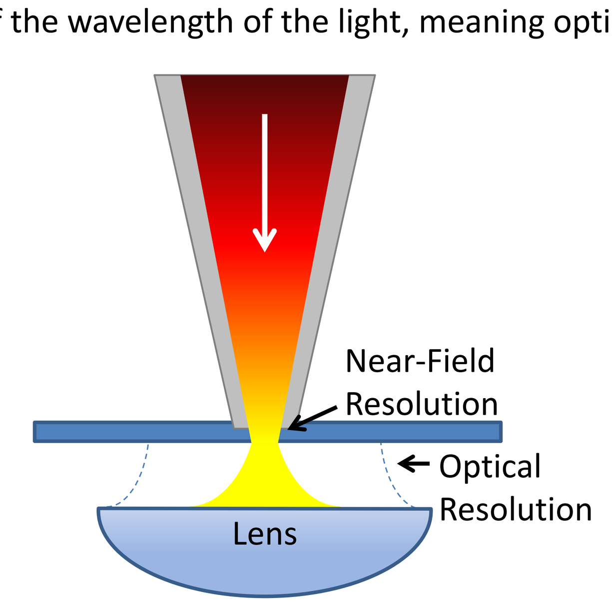
Magneto-Optical Microscopy

One technique for magneto-optical microscopy uses a polarizing beam-splitter to separate the reflected light into its polarization components. In the illustration (right), light is polarized such that the detectors will see the same signal. A shift due to the Kerr effect will change the relative distribution of these components, which is used as the contrast mechanism.



Beating the Diffraction Limit with Near-Field Optical Microscopy

Like all optical microscopes, magneto-optical microscopes are subject to diffraction. The light is continuously spreading out, which limits how tightly a beam can be focused. The resolution limit of a microscope is roughly half the wavelength of the light, meaning optical microscopes can only image objects larger than about 200 nm.



This limit can be overcome using near-field optical microscopy, in which light is delivered to the sample through a tapered optical fiber. In this case, the resolution is limited by the geometry of the tip. The illustration at left shows light incident on a sample from a near-field fiber probe, as compared with light from a lens in a traditional optical microscope.

Objective

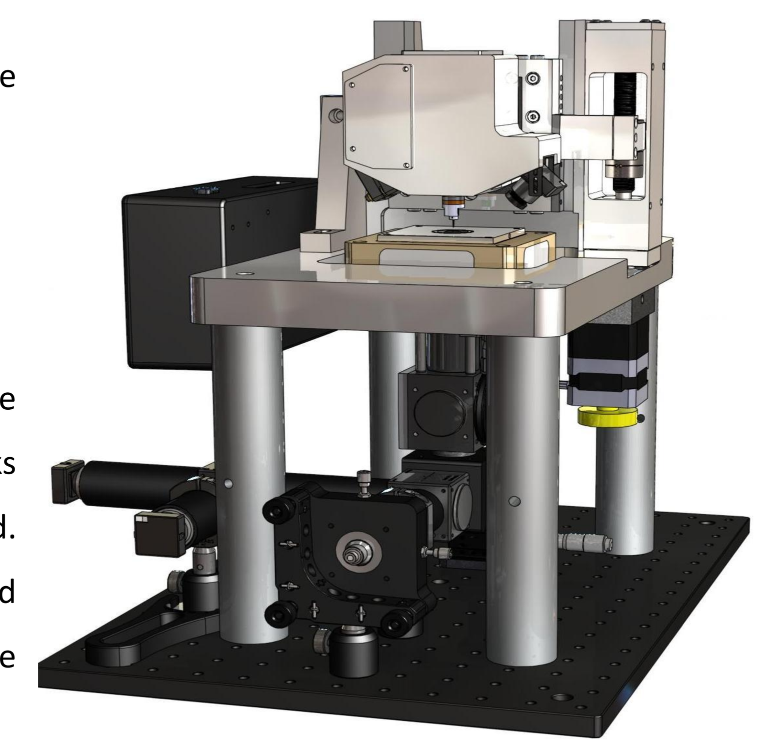
We present an algorithm for predicting the optical response to a near-field probe tip from a generalized multilayer thin film. This will serve as a basis for tip and sample optimization in order to more effectively merge the techniques of magneto-optical and near-field microscopy.

Background

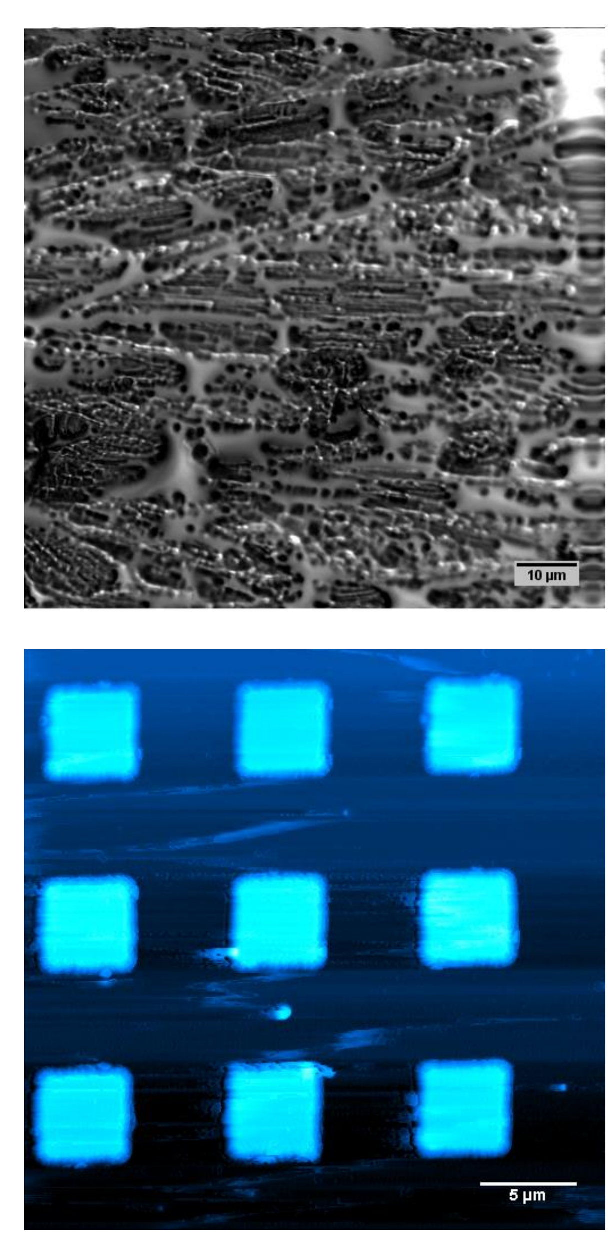
Microscope Development

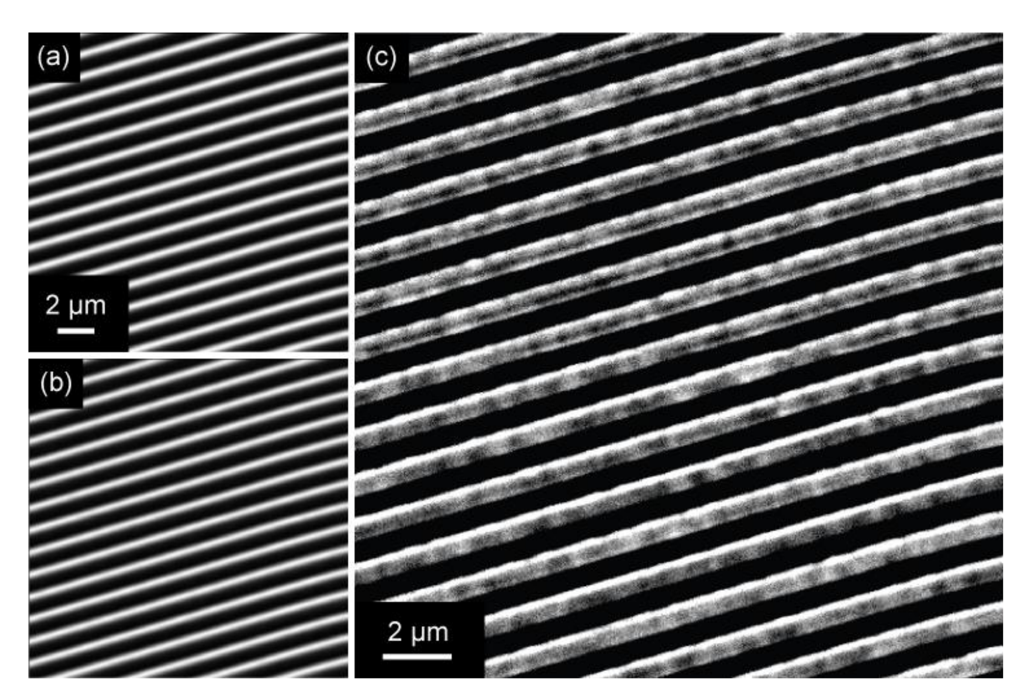
An instrument suitable to our applications would need to be highly versatile, capable of detecting:

- Reflected light intensity (for optical imaging)
- Polarization (for magnetic imaging)
- Topography (for near-field imaging)



We built a microscope (shown at right) with these capabilities. The instrument was designed in SolidWorks (three-dimensional drafting package) and machined by hand. The control is handled by FPGA through LabVIEW and powered by custom circuitry. The design has proven effective for near-field imaging.



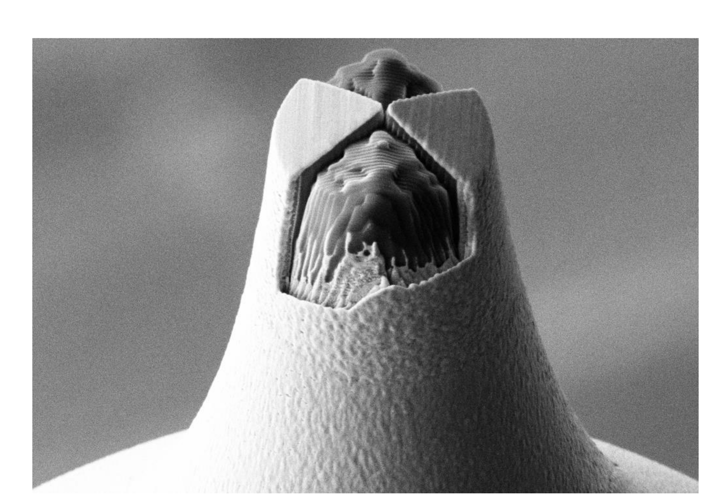


The following images were acquired using this instrument:

- Top Left: A reflection optical image of magnetic glass, Metglas 2065SA1 (Nowak, Lawrence, et al., Rev. Sci. Instrum. **82**, 103701)
- Bottom Left: A topographic AFM (atomic force microscope) image of a calibration grid
- Bottom Right: Kerr image of a magneto-optical disk obtained using a difference method revealing individual data bits. Image (c) is the difference signal between the *s* channel (a) and the *p* channel (b) (Nowak, Lawrence, et al., Rev. Sci. Instrum. **82**, 103701)

Probe Design

The complication in successfully merging the techniques for near-field magneto–optical imaging was the design of the probe tip. This is always an obstacle in near-field microscopy, and more so in our case due to the polarization dependence of magnetic imaging.



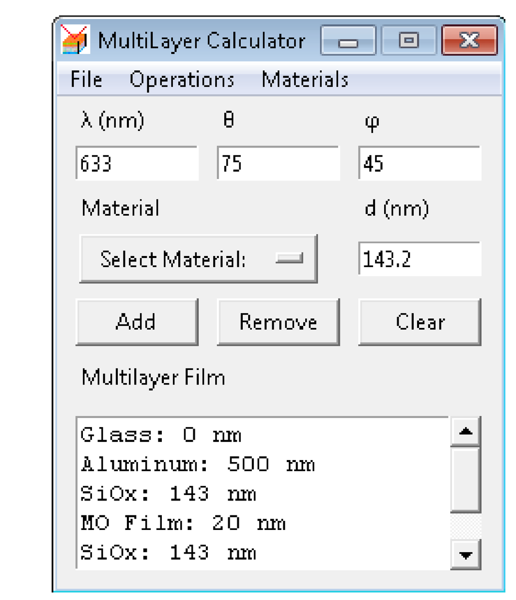
Pictured at right is a possible probe geometry to be analyzed with our algorithm.

Methods

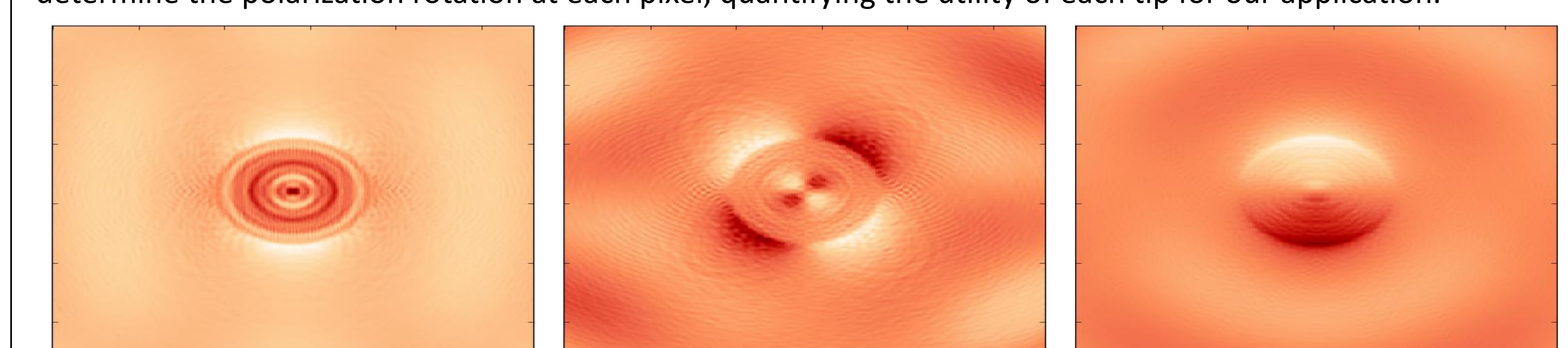
A study of the optical response of a given material requires knowledge of both the incident light and the medium. If the incident light is described by the propagation vector, k, the electric field in the material is defined as E_0, and the optical response of the material is determined by its permittivity, ε, then it can be shown from an analysis of Maxwell's equations that:

$$\left[(k/k_0)^2 + \epsilon\right] E_0 = 0$$

This is the Helmholtz equation, which gives us the relationship between the electric field, the light, and the medium. Our algorithm iteratively solves this equation through every layer of material to determine the properties of the reflected light. The image on the right shows the graphical user interface (GUI) of the program.

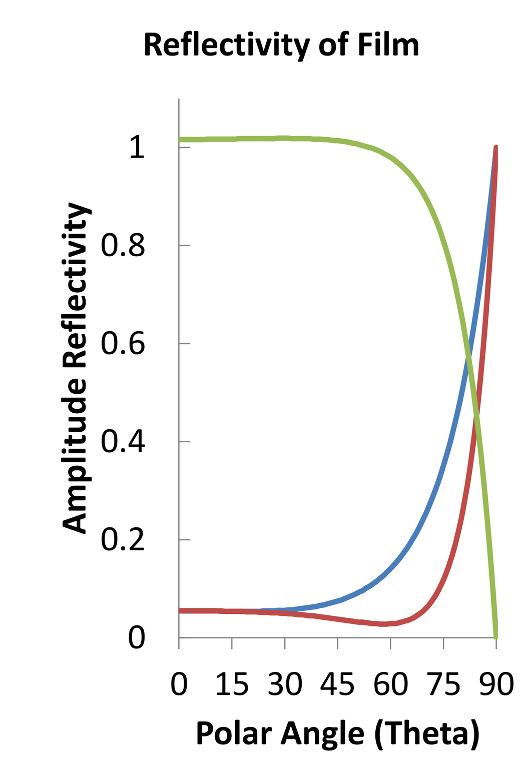


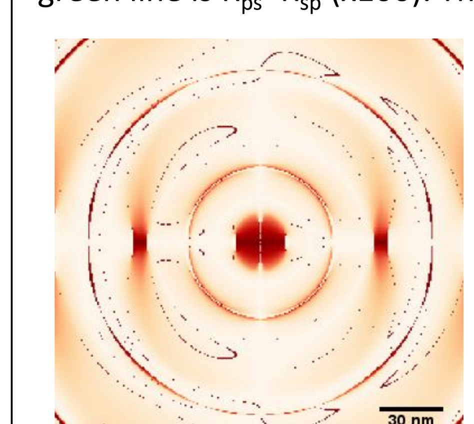
Combined with our ability to model the output of a near-field probe using the finite difference time domain (FDTD) method, we are able to model the optical response from a probe tip. Below, the x, y, and z, components of the electric field from a typical probe are shown (left to right). These can be analyzed with our software to determine the polarization rotation at each pixel, quantifying the utility of each tip for our application.



Results

The algorithm is able to model the reflectivity. The output for a specific film is shown at right. The blue line is R_{pp}, the reflectivity of p-polarized light when the incident light is p-polarized. The red line is R_{ss}, and the green line is R_{ps}=R_{sp} (x100). This is then used to predict the Kerr rotation.





The results from FDTD are then fed to the algorithm to create a map of the Kerr rotation for a given sample and probe. An example from a typical near-field probe is shown at left.

Significance

There is currently a need for better metrology tools for magnetoresistive devices such as spin valves. Near-field magneto-optical microscopy has never been reliable for this purpose due to the complication of probe design. Our work will allow us to optimize near-field probes, which is crucial to the furthering of this technology.

Acknowledgments

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