OPTICAL CHARACTERIZATION OF NANOSTRUCTURED PLASMONIC POLARIZERS

by

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ABSTRACT

This thesis describes techniques involved in the optical characterization of nanostructured plasmonic devices for use as micropolarizing elements. Two types of structures were measured: (1) ultra-high extinction ratio linear micro-polarizers; and (2) the linear structures combined with circular micro-polarizers for full on-chip Stokes polarimetry. An inspection microscope was modified to perform micro-transmission and micro-reflection measurements with precise control of illumination and collection spot size, as well as control over the incident beam collimation and polarization state. The electrical response of micro-polarizing structures fabricated on photodiodes was also characterized using this system. Guidance on how to perform such measurements is presented. Simulation of the optical response was performed and agrees well with experimental results. Recommendations for future development of the equipment, methods, and structures are made.
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CHAPTER 1
INTRODUCTION

Electromagnetic plane waves at optical frequencies can be fully characterized by three parameters: their frequency of oscillation ($\omega$), their propagation direction ($\hat{k}$), and the polarization of their field excitation ($\hat{E}$). There is an additional phase shift, which due to the extremely fast oscillation of the waves themselves, is typically unmeasurable, and therefore not considered further here.

Humans can easily assess both propagation direction and frequency with their eyes, and as such are familiar with the information encoded therein. The polarization state of scattered light can contain equally useful information, such as the orientation of the surface which the light was scattered from[1], or can be used to distinguish light scattered by an object versus lighted scattered by haze[2]. Current implementations of polarization sensitive imaging tend to operate by taking entire images filtered to permit only a single polarization state, and recombining them to make a single polarization image. This often requires spatial multiplexing, where the images are taken by multiple adjacent cameras with similar but different fields of view, or require intermediate optics to divide the light path based on polarization before it reaches detector arrays, which can lead to difficulties in proper image formation[3].

This thesis presents experimental work done in support of an effort to create microplarizers that are wavelength and polarization selective, suitable for fabrication directly onto a CCD array, similar to color filters present inside of digital color cameras. By developing a filtration method that is pixel-sized, we can avoid any of the complications associated with spatially multiplexed methods of polarization resolution, and reuse much of the imaging methodologies used in digital color photography.

The structures examined in this thesis are nano-structured metal films used to generate and transmit light via surface plasmons, which is an electromagnetic wave which propagates
along the surface of a metal-dielectric interface. Because of the boundary conditions on Maxwell’s equations at the surface of the metal, a propagating surface plasmon can only have an electric field, \( \vec{E} \), which is perpendicular to the surface of the metal. This means that any process involving a propagating surface plasmon is inherently polarization selective. By fabricating structures that couple a single linear polarization in different rotated orientations, we can detect different linear polarization states.

In addition to their polarization selectivity, surface plasmons may be used to focus light into a small aperture. If a cap is used to block the directly incident light, it is possible to transmit just the plasmon component, creating a high extinction ratio polarizing transmission structure, as will be shown in this thesis.

One of the most common methods for coupling to surface plasmons is through the use of a grating. Light will be coupled into the plasmon at specific angle and frequency bands, which will be demonstrated in later chapters and is discussed in more detail in Ref. [6]. The amount of power coupled into the plasmon at each frequency and incident angle is a complicated function of the grating aspect, periodicity, and overall size, subject to the intrinsic losses of plasmon propagation.

Combining a grating with an aperture and a cap creates a structure where light can be collected from a large area, filtered by frequency and polarization state, and transmitted through the aperture for collection. An array of these structures could then be fabricated onto a CCD array. The large collection area could be used as a replacement for microlenses which are currently used on CCD arrays to compensate for the interconnection space between detector pixels.

Measuring the wavelength response of such micro-transmission structures is technically difficult. The method chosen in this thesis is to use a white light source, and pass the response into a spectrometer to determine the transmission at different wavelengths. Additionally, in order to minimize background, it is preferable to illuminate only the microstructure being studied. This is done by focusing the incident beam down to a small spot. In an actual
camera (and in simulation), the incident radiation on a detector array is close to plane wave. Attempting to focus light down to a micro-scale, while maintaining beam collimation to test such structures is a challenge. This thesis focuses on the development of an experimental apparatus and procedure for performing optical characterization of such micro-structures. The apparatus presented here can be used for reflection, transmission, and opto-electronic measurements of microscopic structures, while controlling illumination and collection spot size, incident beam collimation, and incident polarization.

1.1 Thesis Organization

Chapter 2 presents an overview of the experimental apparatus and methods used to produce the results of later chapters. It is presented in a format intended to be useful to experimenters that might attempt similar measurements in the future. The remaining chapters are reproductions of peer reviewed publications: Chapter 3 pertains to the simulation and characterization of an ultra-high extinction ratio linear micro-polarizer; Chapter 4 contains an extended discussion of the optimization of the structure from Chapter 3, combining it with circular polarizers for full polarization state characterization, and fabrication of those structures on photodiodes to simulate what the behavior would be on a detector array. My contributions to these papers are as follows:

Chapter 3, which is reproduced from Peltzer et al. [8]: Refining all models presented in the paper to reproduce experimental situations, computing and analyzing the model results, designing and performing all experimental measurements presented, preparing all figures, contributing significantly to the text of the article, and participating in revisions during the editing process.

Chapter 4, which is reproduced from Peltzer et al. [9]: Conceiving the use of spirals as a circularly sensitive structure, performing preliminary modeling of spiral structures, performing simulations and measurements for linear micropolarizers, simulation of off-angle light performance, experimental measurements for spiral structure transmission, performing photodiode measurements, and processing data for those measurements.
CHAPTER 2
EXPERIMENTAL METHODS

All of the measurements presented in this thesis were taken using a modified Nikon Metaphot V microscope, and much of the work of performing the measurements of this thesis was in making the correct modifications to the microscope. The microscope itself was a fairly standard inspection microscope, and the modifications described in this chapter could be applied to other microscopes. A diagram is presented in Figure 2.1 for reference in the following discussion.

![Figure 2.1: Schematic diagram of microscope setup illustrating various light access paths.](image)

The microscope permits optical access to the sample from four different ports: the top illumination port (labeled A in Figure 2.1), the bottom illumination port (labeled B in Figure 2.1), the eyepieces (labeled C in Figure 2.1), and the camera port on the top of the objective column of the microscope (labeled D in Figure 2.1). In the microscope’s original configuration, a filament with a diffuser could be attached to either the top illumination port or the bottom illumination port to illuminate samples. The original design of the microscope was such to give uniform illumination of a given area limited by an aperture which shares the sample image plane. For our purposes, we wanted to be able to control the spot size of the illumination (down to a few microns), as well as control the collimation usually with the
goal of complete collimation. Having a small spot size and well collimated light are typically contrary to one another: as light is focused from a large source to a small point, the light is necessarily coming from many angles. Our solution was to use a small light source far away from the sample, which allows for high collimation and a small target spot size. This is the illumination arm shown in Figure 2.1 labeled F.

The illumination arm was connected to the back ports with an X-Y-φ-θ mount to give complete control of how light entered the microscope. This then allowed control of both the spot location and incident angle of the light on the sample. The arm had a pair of lenses, convex then concave, whose spacing could be adjusted to help control the collimation of the light. There was also a removable polarization control stack, constructed of a linear polarizer, quarter wave plate, and half wave plate. For situations where polarization control of the incident light is unnecessary, the stack was removed, to prevent the 50% intensity loss at the linear polarizer. If the system were to be operated in a fashion where high throughput and polarization control were both needed, it is also possible to generate an arbitrary polarization state using three rotatable wave plates (quarter, half, and quarter), but controlling the polarization in that way becomes more complicated than in the current system, which is why it was chosen.

For transmission measurements, the illumination arm was attached to Point B in Figure 2.1, and light was incident on the sample from below. The camera access port (Label D in Figure 2.1) proved to be an ideal location to connect a measurement arm. An inverted objective was used to recreate the sample image plane at the location of a collection fiber. Because the sample surface is reimaged at the surface of the collection fiber, the collection spot location could be controlled simply by moving the fiber. Aligning this system can be done by illuminating through the collection fiber and bringing the fiber surface into the same image plane as the sample (by moving the fiber up and down). Once this is done, an image of the fiber is visible by viewing through the microscope. Positioning the fiber in the horizontal plane is then used to pick the collection region. Precise measurement control was established
by mounting the fiber in an XYZ adjustable controller. The X and Y adjustment can be relatively coarse, but the Z adjustment needs to be fairly precise, as the depth of focus for the objectives is fairly shallow. Very small collection spots down to 24 µm were possible using this method.

The top illumination port (Point A in Figure 2.1) passes light through a pair of apertures and a set of focusing lenses internal to the microscope, which in its original configuration was used to control the spot size and intensity of illumination on the sample; one aperture shares an image plane with the sample for spot size control, and the other controls the amount of diffuse light reaching the sample. This however does not allow for simultaneous control of the collimation of the light. For reflection measurements, the illumination arm is attached to point A for illumination allowing for better simultaneous control the spot size and collimation. This is much more difficult than in transmission, because the incident light must pass through not only the lens but the objective to reach the sample. When performing transmission measurements, the top illumination port was used with the original microscope light source to illuminate the sample for positioning. Once the sample was in place, a movable beam splitter built into the microscope could be used to remove light incident from the top port.

The illumination arm also featured a removable pick-off mirror of the same structure as the turning mirror below the microscope, whose output can be fed into a commercially available polarimeter (Thorlabs TPX 1000 in our case). This allows us to check the polarization state of the incident light as it would reach the sample.

If the primary goal of illumination through the bottom arm was a very small spot size rather than a highly collimated beam, a focusing lens (labeled E in Figure 2.1) was inserted just below the sample mount. The lenses in the input arm could then be adjusted to minimize the spot size. There is some sacrifice of polarization control, as the focusing lens does not perfectly preserve the polarization of the incident light. Linear polarization filtering can overcome this by placing a linear filter between the last lens and the sample, which we did
for high extinction ratio linear measurements.

The eyepiece ports (Label C in Figure 2.1) gain optical access to the sample via a movable, internal 70/30 beamsplitter that is shared with the camera port (100% of light reaches the eyepieces without the beamsplitter, 30% when it is inserted). While an image plane of the sample can be recreated using the eyepieces for collection, it was more structurally sound to build the collection apparatus at the camera port rather than at the eye pieces. Still, visual access to the system is useful for alignment and for imaging. To take sample snapshots, a digital camera was mounted at one of the eyepieces. The other eye piece was used for standard viewing. It is worthwhile to mention that, as optical access from this path can never fully be removed, blocking off the eyepieces during measurement may decrease stray light entering the system.

These modifications come together to allow for control of the illumination polarization, spot location, illumination collimation, and some control over the angle of incidence of the beam. The collection spot size is also independently controllable. These controls allow for sample characterization on a local scale, which opens up a variety of new opportunities for study.

2.1 Quantitative Transmission Curve

One of the key measurements in Chapter 3 is the transmission of a filter structure as a function of wavelength, which was compared to simulation. The results of this measurement are shown in Figure 3.3. The goal was to verify the extremely high simulated extinction ratios for this structure. To verify this extinction ratio, we need to be absolutely certain that all measured light in the ”blocked” alignment is coming from the sample, as any sort of room contamination could be mistaken as transmitted light, leading to a much lower extinction ratio.

Removal of the background light was done via a build-up method of isolating and removing stray light. Initially, an exposure was taken with the light source turned off, and the resulting spectrum was scrutinized for light sources, which if found were if possible covered.
Some examples were power indicator lights in the room and some stray light leaking in from the door. Once these contamination sources were minimized, the light source for the experiment was activated, but the sample path was blocked using the selective beamsplitter. The background measurement was repeated, and this time the search focused on places that light was scattering out of the intended optical path, and then recollected in the spectrometer. This was resolved mostly by encasing the light path with black felt everywhere possible. Once any unintended scatter was minimized, we were more confident that collected light had actually passed through the sample.

The incident light was focused to a minimum spot size using a lens placed just below the sample, and then the divergence lenses were adjusted to ensure that the focus fell at the sample plane. The larger the spot size, the more likely other features outside the actual structure would scatter light that might find its way into the spectrometer. By focusing the light, we limit the spatial extent of the light incident on the surface to a circle approximately 150 µm across.

The choice to focus the light meant that the incident light was not fully planar, but the effect of non-planar light was simulated, and the extinction ratio maintained a very high value for the angles of light used.

To align the illumination and collection spot, a translucent metal film was placed under the microscope. Light was fed back through the collection fiber as well as illuminating from beneath. In this way, both the image of the collection spot and the illumination spot could be viewed at the same time. See Figure 2.2(b). The collection spot was centered in the illumination area and the surface of the fiber was placed in a conjugate image plane with the sample. This allows the use of the collection fiber itself as a limiting aperture. Collection spot size was limited to ~24 µm. Once aligned, the actual sample was put in place, and the collection spot was used to ensure the sample was aligned with both the illumination and collection spots. Illustrative images of this process, showing the spot size relative to the structure of interest are presented in Figure 2.2.
Figure 2.2: (a): SEM image of sample structure for comparison. (b): Image of focal plane showing both illumination spot (large) and collection area (small) as imaged on a translucent film. (c): Image of illuminated collection fiber on surface of sample with alignment marks for patterned structure. (d): Image of patterned structure illuminated in transmission.
For high linear extinction ratio measurements, the polarization state of the incident light was controlled using a single linear polarizer placed just above the last focusing lens: in this way we avoid any birefringence or depolarizing that may occur from passing through the lenses. This allows less general control of the polarization state than the arbitrary polarization stack, but is sufficient for the desired linear polarization.

The incident power on the structure was measured using the transmission through a square aperture whose area was comparable to the total area of the structure. Because the structure is much larger than the wavelength in question, we can neglect scattering from the edges and treat the collected light as proportional to the area of the square aperture. Using this, we computed the percent transmission through our structure.

A background is measured by taking the transmission measurement on a prepared space on the sample where no device was actually fabricated. This allows us to capture any possible contamination from nearby alignment marks, (which should be outside of the collection area, but could contribute via secondary scattering) along with any direct leakage through the theoretically opaque surrounding metal. This measurement also captures any light that is being generated from other sources in the room.

The polarization state was considered TM, when the signal was maximized visually, and then TE was acquired by rotating the polarizer 90 degrees from TM alignment. In principle, the TM signal could have been located by quantitatively maximizing the transmission measured on a short time scale, but the spectrometer shutter available was not time stable for the short times necessary for the larger TM signals, and using longer time scales for iterative methods of alignment can be extremely time consuming.

After background was subtracted from both TE and TM transmission curves as a function of wavelength, the resulting curves were compared. Because the models for the system do not indicate the same sort of structure in the TE mode as the TM, and because even a very slight error in angular position would create a large TM signal compared to TE, we fit the TE measured data as a mixture of the TE and TM data and eliminating the TM component.
to retrieve the true TE signal. For this measurement, the true TE signal was noise limited for wavelengths above 600 nm, but had good agreement with theory at lower wavelengths giving confidence in the measurement procedure. Measuring high extinction ratios requires long exposures for the TE measurement due to the weakness of the signal. Times of 10 seconds were sufficient for TM to provide an adequate signal, but exposures up to 4000 sec were used in attempts to characterize TE transmission effectively.

Alternatively, the extinction ratio was also calculated by taking incremental spectra every 5 degrees of rotation around a full 360 degrees, and then fitting a sinusoidal curve to the transmission as a function of angle. By choosing either a single wavelength or integrating over a region of interest, a count rate at each angle can be computed. The data can then fit a model of the form

\[
\text{Count rate} = \text{TM} \cos(\theta - \phi)^2 + \text{TE} \sin(\theta - \phi)^2 + \text{BG}
\]

with \( \theta \) as the polarizer angle, TM, TE, BG and \( \phi \) as free parameters, respectively representing the TM transmission, TE transmission, unmodulated background transmission, and \( \phi \) as the orientation of the polarizing element relative to the polarizer angle. The values calculated are much more reliable when compared to an aligned-crossed comparison (which is the equivalent of fitting this model with data points for \( \theta = \{0, 90\} \), but the generation of many additional data points necessarily takes additional time.

2.2 Measurement of Structures on Photo-diodes

The second essential measurement made to characterize the function of the nanoscale polarizers was to measure structures fabricated onto photodiodes, and examine the generated current as a function of incident linear light polarization. To achieve this measurement, a lock-in scheme was chosen, where the incident light would be modulated through the use of a chopper, and then a lock-in amplifier would be used to pick out the magnitude of the signal that matched frequency with the chopper. This allows the generation of curves such as Figure 4.10(b).
The chopper can be mounted on the table before entering the rest of the system by coupling out of the fiber via collimator into the open air for chopper modulation, and then back through another collimator into a second fiber. Alternatively, it can be suspended between the illumination fiber and the objective. The first method suffers from additional coupling losses, but this approach was found to be preferable to the difficulties of suspending the rotating chopper horizontally above the microscope.

To measure the signal generated by the diode, it is necessary to connect the diode to an electrical circuit. In practice, this means using a pair of micromanipulators (see Figure 2.3) to land sharp electrical contacts onto termination pads on the sample, which were created during the chip fabrication. Because of the small scale of the actual features, the pads are located some distance away, at the end of metal lines run out from the structures. Using the micromanipulators to get good electrical contact was one of the more challenging steps in this measurement.

Because of the small feature size, it was impossible to simultaneously view the entire array of structures and to focus on one structure in particular. This made unambiguous identification of the probed diode difficult - the most efficient way was to locate the diode of interest by putting the contact pad into the field of view in the microscope and then tracing the connection line in to the corresponding structure. While looking at the contact pad, the microscope was used to help land the probe tip on the contact.

Landing the probe tip on the contact is difficult to do correctly. The probe tips are necessarily sharp, to limit their spatial extent on the chip, which can lead to problems as they tend to punch through the thin contact layer if too much force is applied, but will not create an effective contact without sufficient force. The probe tips are also bendable enough that they can cause the chip to shift about if too much force is applied. Proper control of the tip angle compounds this problem: if the tip angle is too shallow, the tip tends to contact the chip across a long distance and deflect heavily, while using a steep tip angle makes actually fitting the tip under the microscope objective difficult. It is important to make sure that
your objective is not in contact with the probe during landing, as it would cause the probe to bend, which would move the tip of the probe after the objective is moved away, which would change the contact point. Long working distance objectives were used to alleviate this.

Maintaining good electrical contact is also difficult because the probes need to remain stationary relative to the chip, which means that they must be able to move along with the sample as it is translated underneath the microscope. This necessitated the expansion of the sample stage to include a supporting area for the probe micromanipulators, which in turn increased the weight of the sample stage; this caused the sample stage to drift downwards over time. This problem was somewhat alleviated by drilling holes in the new stage (which decreased its weight).

Once electrical contact was achieved, the sample was translated so that the target sample could be illuminated. For these measurements, there was little extra gold coverage around each structure, as can be seen in Figure 2.4(B), leading to some light leakage around the structures, since adjacent structures needed to be electrically isolated. The sample magni-
Figure 2.4: (a) Overview of fabricated diode array. The gold lines leading out of the frame extend out to contact pads along the edge of the chip. (b) Image of diode-fabricated structure with illumination spot. Bare silicon is visible beside the gold patterned structure.

Polarization control was achieved by placing a high ER polarizer directly below the microscope objective and above the sample, which could be rotated. This was done through the use of a custom collar for the objective, with one stationary segment which mounted to the objective, and another which was free to rotate about the objective holding the polarizer. The rotating collar segment was scribed with 5 degree increments, while the stationary mount was scribed with a Vernier scale so as to, in principle, allow rotations as fine as one degree. In practice, the friction-based fit of the rotating collar precluded that degree of fine control, as the stick-slip nature of the hold tended towards jumpy movement.

2.3 Other Experimental Insights

The experimental apparatus needs a time-stable broadband source of white light. This was achieved by using a fiber coupled Ocean Optics LS-1 light source. The light source was placed inside of a velvet-lined box to keep stray light from scattering into the detector, and this box was fitted with a cooling fan so as to ensure the temperature stability of the source.
The cooling fan may have been unnecessary, but the velvet box was important to contain stray light from spreading into the room, as some light escapes when coupling to the input fiber.

When aligning the system to use the lower light port for illumination, and the camera port for collection, as is done during small spot transmission measurement, it is often useful to use a translucent sample as an alignment base, so as to image the light passing both directions at once. A thin sheet of tissue paper is often ideal for this, as the diffuse surface does not confuse the transmitted light with a specular reflection.

When attempting to ensure that the illumination is normal to the surface, it is often instructive to watch the progress of the spot as the sample plane is moved out of focus. Because the beam will diverge uniformly around its own optical axis, if the illumination spot moves laterally as the sample plane is moved out of focus, that gives a sense of how the beam is angled.

The commercial polarimiter used in this thesis was invaluable for the timely characterization of incident beams. The polarimiter was unsuitable, however, for the characterization of the output beams because the sensitivity of the polarimeter was not enough to detect the weak output signals. If direct detection of output polarization is desired, a different method of measuring the polarization would have to be explored.
CHAPTER 3

ULTRA-HIGH EXTINCTION RATIO MICROPOLARIZERS USING PLASMONIC LENSES

A paper published in *Optics Express* [8]¹

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3.1 Abstract

The design of a new type of plasmonic ultra-high extinction ratio micropolarizing transmission filter is presented along with an experimental demonstration. A pair of dielectric coated metal gratings couple incident TM polarized light into surface plasmons, which are fed into a central metal-insulator-metal (MIM) waveguide, followed by transmission through a sub-wavelength aperture. Extinction ratios exceeding $10^{11}$ are predicted by finite element simulation. Good absolute agreement for both the spectral and polarization response is obtained between measurement and simulations using measured geometric parameters. The filters can be easily fabricated and sized to match the pixel pitch of current focal plane arrays.

3.2 Introduction

Polarization resolved imaging of light plays an important role in a number of applications [10, 11]. It can yield information about the orientation, material type, and roughness of a surface [1, 2]. Early embodiments of this concept involved time-sequenced serial or amplitude-division parallel polarization filtering in the aperture plane of a conventional imaging system [12]. More recent designs involve micropolarizing elements that are directly integrated into the

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¹Used with permission. See Appendix 6
²Primary Author. See Section 1.1 for detailed description of role.
³Supervised simulation and measurements performed at Colorado School of Mines.
⁴Advised efforts at Colorado School of Mines,
⁵Advised measurements and other efforts at Colorado School of Mines
⁶Supervised fabrication of structures at ITN Energy Systems.
structure of individual pixels of detector arrays. These have been proposed and demonstrated using liquid crystal micropolarizing elements[13], metal nanowire and nanoparticle polarizers[14–22], and polymer micropolarizers[23]. To enable very sensitive measurements, high extinction ratios along with high transmission for the desired polarization state are needed.

Here we present simulation and experimental results for a new plasmonic linear micropolarizer with extinction ratios which can be made arbitrarily high constrained only by processing considerations, where the undesired linear polarization state is limited by direct transmission through a thick metal film. Example structures are demonstrated with near-field extinction ratios exceeding $10^9$.

3.3 Overall Device Structure

The plasmonic micropolarizer consists of a metal film fabricated with a linear aperture in a central cavity that is surrounded by linear gratings parallel to the aperture. This is shown in cross section in Figure 3.1(a). The aperture and gratings are covered with a transparent dielectric layer to form a surface plasmon slab waveguide that supports only TM polarized modes. This part of the device is based on a structure that we have previously described, which exhibits enhanced transmission[5]. TE transmission is removed by the addition of a metal cap that covers the aperture and forms a metal-insulator-metal (MIM) waveguide. The gratings couple light into surface plasmons, and the cavity width ($w_c$) is adjusted to obtain constructive interference between the surface plasmons and incident light at the edge of the cap. TE modes are cut off due to the sub-wavelength dielectric thickness in the MIM waveguide, while the TM modes have no cutoff[24].

The micropolarizer behaves like a plasmonic lens, concentrating incident TM light over a large collection area into a sub-wavelength aperture where it is transmitted (see Figure 3.1(b)). The characteristics of the concentration and the effective spectral range are adjustable by varying the extent of, and feature size within, the device. Large collection area structures transmit high absolute power over a narrow bandwidth, while smaller struc-
Figure 3.1: Plasmonic Micropolarizer Structure: (a) Central structure of linear micropolarizer showing aperture, cavity and first grating period. The taper angles of the aperture and gratings along with the dielectric profile were chosen to match the fabricated structures. (b) Simulated time average power flow through the aperture of a structure with 635 nm period input gratings having 19 grooves per side.

structures exhibit high transmission efficiencies over a wider bandwidth. By pixel-pitch matching to a photodiode or CCD focal plane array, measurement of the first three components of the Stokes vector (corresponding to linear and unpolarized states) can be obtained with a four pixel super-pixel. An illustration of this with an inset of the instantaneous magnetic field is shown in Figure 3.2. One pixel may be replaced by a micropolarizer sensitive to circular polarization, which is currently being developed and will be discussed in a future publication. This would yield the complete Stokes vector.

3.4 Experimental Verification

The devices used for the experimental demonstration were fabricated on polished microscope slides coated with 200-250 nm of gold on top of a 2.5 nm titanium adhesion layer. All patterning was done by electron beam lithography in a JEOL 840 scanning electron microscope with NPGS software. In the first patterning level, linear apertures and alignment marks were defined in the positive resist PMGI (polydimethylglutarimide) and cut
completely through the metal using broad beam Ar ion milling. In the second patterning level, gratings with 19 grooves per side and the central cavity were defined in the positive resist PMMA (polymethylmethacrylate) and cut partially into the gold surface using Ar ion milling. For the samples reported here, the groove and cavity depth were approximately 35 nm with grating period and cavity width as variable parameters. This was followed by blanket deposition of SiO$_2$ using plasma enhanced chemical vapor deposition. In the final patterning level, a metal cap was fabricated over the aperture using a lift-off process. The alignment marks were also covered at this processing level to minimize the transmission of unfiltered light. Geometrical parameters (grating period and depth, cavity width, aperture width and position, cap width and position) of the fabricated structures were measured using a combination of scanning electron microscopy and atomic force microscopy.

Experimental far-field spectra were collected using an optical microscope configured for transmission measurements coupled to an Acton 300i spectrometer with a Princeton Instruments Spec-10:100BR liquid nitrogen cooled silicon CCD array detector. A fiber coupled tungsten halogen lamp provided white light for an input arm which included divergence control lenses and a rotatable high extinction ratio polarizer (Thorlabs LPVIS050). Linearly
polarized white light was incident on the air side of the structure and collected with a long working distance objective (N.A.=0.5) after transmission through the polarizing element and 1mm thick glass substrate. The ~24 µm collection spot size was smaller than the 50µm pattern length and comparable to the pattern width. The collected light was focused onto the end of an optical fiber positioned in a conjugate relationship to the sample plane. The opposite end of the fiber was optically coupled to the entrance slit of the spectrometer. Raw spectra were background subtracted and normalized to a white light measurement made with no sample in place to give absolute transmission.

Two-dimensional finite element simulations were compared to experimental results. The grooves were assumed to be infinite in length in the models, which is an appropriate approximation as the lengths of the grooves are much longer than pertinent lateral dimensions. Simulations were performed with the commercial finite element analysis package, COMSOL Multiphysics, which solves the frequency domain Helmholtz equation for the electric and magnetic fields. Spectroscopic ellipsometry of fabricated structures was used to determine the optical constants and thickness of the deposited SiO₂, along with optical constants of the deposited gold for use in simulation. The base gold thickness was determined to be 242 nm by fitting to the measured transmission through the smooth gold near the pattern, which is in reasonable agreement with a measurement of 230 nm performed using a stylus profilometer on a separate witness slide. The models were truncated using perfectly matched layers[25]. The far-field electric field was calculated using the Stratton-Chu formula[26]. The far-field was then integrated over an angle appropriate to the collection angle of our measurement objective (NA=0.5) for comparison to experimental data.

Structures were fabricated with 19 grooves in each of the two gratings with 500 nm period and variable cavity width. The far-field transmission spectrum of a representative structure is shown in Figure 3.3(a) for TM polarization (example SEM images of structure are shown in inset). The simulated and measured far-field TM transmission show good agreement in terms of peak location and absolute transmission efficiency. For this structure, 1.07% and
1.53% of the light incident on the entire structure was measured and simulated, respectively, to be collected in the far-field. Further optimization yields much higher efficiencies (see Figure 3.4(a)). This demonstrates the ability of the structure to focus light from a large collection area into the sub-wavelength aperture.

Figure 3.3: Measured and Simulated Spectral Response: Model Validation and Ultra-High Extinction Ratio Prediction. (a) Measured and simulated absolute TM transmission through a high-selectivity structure with 500 nm period input gratings having 19 grooves per side. The inset shows a representative SEM image of a complete structure and an off-angle detail of the central region. (b) TE transmission with the curve labeled ‘TE simulation’ estimating power collected by the microscope objective, and the ‘TE near field’ curve simulating all of the power exiting the aperture. (c) TM/TE extinction ratios. The measurement is background limited for wavelengths >600 nm.

Two different simulated TE transmission spectra along with the measured TE transmission for the same structure are shown in Figure 3.3(b). The primary contribution to the far-field TE signal is, in fact, direct transmission through the gold film with the value increasing
toward the green due to an interband transmission at about 470 nm wavelength[27]. The TE near field shown in Figure 3.3(b) is the simulated power exiting the aperture. The near field TE transmission through the aperture is many orders of magnitude lower than the far-field transmission because the cap increases the effective metal thickness reducing direct transmission near the aperture. While the TE measurement agrees well with the far field simulation at short wavelengths, at longer wavelengths there is a deviation between the two, because the measurement was background limited above about 600 nm. The flat background indicates white light contamination.

The TE measurement in Figure 3.3(b) was performed with an illumination spot roughly twice the size of the grating structure. Increasing the illumination spot size with a constant collection spot size (roughly the size of the structure) causes the flat background to increase uniformly while the short wavelength transmission remains unchanged. This leads to the conclusion that the flat background is due to transmission away from the structure through pinholes in the metal film. The light undergoes multiple reflections inside the glass substrate until it is scattered into the collection optics at the aperture (the major scatterer on the output side of the gold film). The measured far-field, simulated far-field, and simulated near-field extinction ratios (ER) are shown in Figure 3.3(c). The simulated near-field extinction ratio peaks at $1.1 \times 10^9$ and remains near that value at longer wavelengths, and is limited at low wavelengths by the high direct transmission through the gold film. The good agreement between TM simulation and measurement, and TE simulation and measurement at low wavelengths confirms the near-field simulated behavior of these structures.

3.5 Structure Optimization

Because measured TE transmission at higher wavelengths is limited by pinholes and direct transmission through the metal film itself, improving film quality, thickness or using a metal with lower skin depth will allow for increased extinction ratios. Near the peak wavelength at 700nm, in the MIM waveguide the propagation length of the lowest TE and TM mode are 33nm and 2.5um, respectively. The skin depth of gold is 14.4nm. Therefore, if
the transmission through the MIM waveguide dominates, an order of magnitude in extinction ratio can be gained by adding 77nm of length on the cap while decreasing TM transmission by only 3% of its value. If direct transmission through the metal is the limiting factor, for roughly every 33nm of additional gold thickness an order of magnitude in ER will be gained.

Aluminum has a small skin depth compared to gold (and silver) over the entire visible and IR wavelength range, but also higher loss. Simulations were performed replacing the gold substrate with a 200nm aluminum/50nm gold stack, and replacing the gold cap with a 50nm gold/100nm aluminum stack. The cap was also widened by 400nm. The peak near field and far field extinction ratios increased to $2.39 \times 10^{11}$ and $7.41 \times 10^{10}$, respectively. The peak TM transmission maintained a high value, decreasing only from 14.0% to 9.5%. This process can be carried further allowing essentially arbitrarily large theoretical extinction ratios, which in practice will be limited only by fabrication imperfections such as surface roughness, or the finite length of the device (long MIM structures will be necessary for the highest extinction ratios). For improved performance into the blue, the gold in this structure could be replaced with silver.

Figure 3.4: Tunable Bandwidth and Transmission Efficiency. (a) Simulated transmission efficiency for structures with 635 nm grating period and variable number of grooves. (b) Enhancement factor as defined in the text for the same structures. All presented structures were modeled using an 800 nm cap width, a 2000 nm cavity, and a 635 nm periodicity. The 2 and 4 groove models use an $h$ value of 45 nm, while the 20 groove model uses an $h$ value of 20.
The structures can be further optimized to realize very high transmission efficiencies, up to 29.9% for the desired polarization state. Figure 3.4(a) contains transmission spectra from simulated structures having different numbers of grooves in the gratings demonstrating how the band width and transmission efficiency can be tailored. Increasing the number of grating grooves reduces the bandwidth, but also reduces the transmission efficiency; absolute power increases as the collection area of the structures increase, but due to the increased area of the device, the efficiencies decrease. Figure 3.4(b) replots the groove number simulations as an enhancement factor, which is defined as the transmitted power divided by the power transmitted by a bare aperture. Enhancement factors of more than 12 were achieved for 20 grooves. This demonstrates how the structure collects more power as the collection area is increased.

All gratings are sensitive to the incoming lights angle of incidence. The spectral performance of a high efficiency, 4 groove design was examined for incident angles from 0 to 20 degrees. Transmission efficiency decreases from about 32% to 15% and the FWHM increases slightly as the incident angle is increased to 4 degrees. For incident angles of 6-20 degrees, the transmitted signal splits into two distinct peaks with maximum efficiency remaining around 15%. However, because of the MIM cutoff based polarization filtering, there is no significant change in extinction ratio over all incident angles.

The wavelength of the peak transmission is also tunable by scaling lateral dimensions. Experimental results are shown in Figure 3.5 for structures fabricated by simple geometric scaling of the grating period, cavity width and cap width. The inset shows the peak wavelength vs. grating period. Because only lateral dimensions were varied, structures for filtering different spectral bands may be fabricated using the same lithography steps, making this structure amenable to large scale integrated fabrication for simultaneous color and polarization micro-filters.
Figure 3.5: Tunable Peak Wavelength. Measured TM transmission curves for three structures whose linear dimensions (cavity width and grating periodicity) have been scaled to shift the transmission peak. The blue curve was fabricated with a period of 450 nm and a cavity width of 2070 nm. The black curve has a period of 500 nm and a cavity width of 2300 nm, and the red curve has a grating periodicity of 575 nm and a cavity width of 2650 nm. (inset) plot of peak wavelength vs grating period showing approximate linear scalability.

3.6 Applications of design

The overall dimensions of these micropolarizers can be matched to the pixel size of CCD or CMOS focal plane arrays. The design presented here has distinct advantages over alternate approaches. The demonstrated extinction ratio is already a factor of ten higher than alternatives operating at similar wavelengths[16, 21], and potential extinction ratios are far higher than easier to fabricate infrared polarizers[20]. While alternate approaches provide only polarization filtering, this design combines spectral and polarization filtering into a single structure, which has distinct advantages in applications such as biomedical imaging[28] or advanced polarimetric image reconstruction[29]. Micropolarizers are commonly integrated with a buffer layer between the micropolarizers and detector elements, resulting in optical cross-talk that can greatly decrease the precision of polarization selectivity[30]. The design presented here can be directly fabricated into the Ohmic contact metallization of a detector, completely eliminating optical cross-talk produced by the filter. Alternatively, the basic
design of Figure 3.1 can be modified to include a grating structure on the output surface of the metal, which can cause beaming from sub-wavelength apertures maintaining a small spot size many wavelengths from the output face[31]. Because the micropolarizer focuses the light to a small spot size, sensor sizes may be reduced with a corresponding decrease in noise and increase in response speed compared to alternate approaches. Also, because of the plasmonic lensing effect, the microlens array commonly used to increase collection fill factor in commercial focal plane detector arrays may be eliminated.

3.7 Conclusion

In summary, this paper presents simulation and experimental results demonstrating a spectral and polarization micro-filter, which can be integrated onto focal plane arrays of detectors. These micro-filters have ultra-high extinction ratios, controllable spectral behavior, and can be easily manufactured using standard lithography techniques.

3.8 Acknowledgements

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CHAPTER 4
PLASMONIC MICROPOLARIZERS FOR FULL STOKES VECTOR IMAGING

A paper published in SPIE Proceedings\cite{9}\footnote{7}
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4.1 Abstract

Polarimetric imaging using micropolarizers integrated on focal plane arrays has previously been limited to the linear components of the Stokes vector because of the lack of an effective structure with selectivity to circular polarization. We discuss a plasmonic micropolarizing filter that can be tuned for linear or circular polarization as well as wavelength selectivity from blue to infrared (IR) through simple changes in its horizontal geometry. The filter consists of a patterned metal film with an aperture in a central cavity that is surrounded by gratings that couple to incoming light. The aperture and gratings are covered with a transparent dielectric layer to form a surface plasmon slab waveguide. A metal cap covers the aperture and forms a metal-insulator-metal (MIM) waveguide. Structures with linear apertures and gratings provide sensitivity to linear polarization, while structures with circular apertures and spiral gratings give circular polarization selectivity. Plasmonic TM modes are transmitted down the MIM waveguide while the TE modes are cut off due to the sub-wavelength dielectric thickness, providing the potential for extremely high extinction ratios. Experimental results are presented for micropolarizers fabricated on glass or directly into the Ohmic contact metallization of silicon photodiodes. Extinction ratios for linear polarization

\textsuperscript{7}Used with permission. See Appendix 6
\textsuperscript{8}Performed all characterization experiments. See Section 1.1 for detailed description of role.
\textsuperscript{9}Performed circular micropolarizer simulation
\textsuperscript{10}Performed RGB filter simulations, Structure optimization simulations
\textsuperscript{11}Supervised simulation and measurements performed at Colorado School of Mines.
\textsuperscript{12}Advised efforts at Colorado School of Mines
\textsuperscript{13}Advised measurements and other efforts at Colorado School of Mines
\textsuperscript{14}Participated in much of the writing of much of the text of the paper and supervised the overall project
larger than 3000 have been measured.

4.2 Introduction

Polarization-resolved imaging of light plays an important role in a number of applications, yielding information about the orientation, material type, and roughness of a surface\cite{1, 2, 11}. Imaging polarimeters examine the polarization state of light reflected or emitted from objects, providing information complementary to the intensity and wavelength data provided by most cameras. A recent review by Tyo provides a good introduction to the various camera designs used in passive imaging polarimeters\cite{10}. Early embodiments of this concept involved time-sequenced serial or amplitude-division parallel polarization filtering in the aperture plane of a conventional imaging system\cite{12}. Advances in nanofabrication have led to increased attention to division of wavefront focal plane systems in which an array of micropolarizing elements is monolithically integrated directly on a focal plane array (FPA) sensor. The mechanical robustness, permanent polarizer-to-sensor alignment, and potential for low-cost fabrication provide significant advantages for this approach, while recent advances in image reconstruction algorithms mitigate the artifacts that arise from each pixel looking at a slightly different part of the scene\cite{32, 33}. Division of wavefront focal plane systems have been proposed and demonstrated using liquid crystal micropolarizing elements\cite{13}, metal nanowire\cite{20, 22, 34} and nanoparticle polarizers\cite{19}, and polymer micropolarizers\cite{16, 23}. Imaging systems have been demonstrated from visible\cite{18} to long-wave IR\cite{35} spectral bands. To enable very sensitive measurements, high extinction ratios along with high transmission for the desired polarization state are needed. These systems have examined only the linear polarization components of the Stokes vector due to the difficulty in fabricating micropolarizing structures sensitive to circular polarization.

In bulk optics, circular polarization is typically examined using a quarterwave plate in combination with a linear polarizer. The birefringent materials typically used to make quarterwave plates are difficult to fabricate on a micro scale. Liquid crystals integrated with metal wire-grid linear polarizers provide one approach to obtaining the circular polarization signa-
ture and are under development for imaging applications[36]. Several alternative approaches for fabricating wave plates have been reported. A dielectric grating with period less than half the operating wavelength acts as a birefringent material that can be fabricated into a quarterwave plate[37]. These require relatively large aspect ratios along with precise control of the duty cycle and groove depth for quarterwave operation. Subwavelength metal gratings have also been shown to behave as wave plates[38], as have dielectric nanorods with a zigzag profile fabricated by off-angle deposition with periodic substrate rotation[39]. Elements sensitive to circular polarization have been reported in an assortment of antenna analogue and asymmetric plasmonic structures, including meanderlines[40], hole arrays[41], cross-shaped antennas[42], and elliptical[43] or single spiral gratings[44] with a central aperture.

Here we report on an easily fabricated micropolarizing filter design that can be tailored for linear[8] or circular[45] polarization sensitivity as well as spectral response through variations in horizontal geometry. The basic structure can be tuned to operate from blue to IR or even THz spectral ranges through geometric scaling and choice of appropriate materials. Experimental results will be presented for micropolarizers fabricated on glass or directly into the Ohmic contact metallization of Si photodiodes. Linear extinction ratios over 3000 have been measured. Good absolute agreement for both the spectral and polarization response is obtained between measurements and simulations using measured geometric parameters.

4.3 Micropolarizer Design and Simulation

The basic filter structure is shown in the cross section in Figure 4.1a. The filter consists of a patterned metal film with an aperture in a central cavity that is surrounded by gratings. The aperture and gratings are covered with a transparent dielectric layer to form a surface plasmon slab waveguide that supports only TM polarized modes. A metal cap covers the aperture and forms a metal-insulator-metal (MIM) waveguide. The gratings couple light into surface plasmons, and the cavity width is adjusted to obtain constructive interference. Structures with linear apertures and gratings provide sensitivity to linear polarization, while structures with circular apertures and spiral gratings give circular selectivity. An optional
metal side mirror reflects outwardly propagating surface plasmons back toward the aperture to increase the efficiency. Figure 4.1b shows the 2D simulated time average power flow (Poynting vector) for a linear structure with no side mirrors. Plasmonic TM modes propagate down MIM waveguides with arbitrarily thin dielectric layers, while TE modes are cut off by the subwavelength dielectric thickness with exponential attenuation. This provides the potential for extremely high linear extinction ratios. Spiral gratings, such as the Archimedean spiral of Figure 4.1b, or exponential spirals, provide direct sensitivity to circular polarization.

![Figure 4.1](image)

Figure 4.1: (a) Cross-sectional schematic, (b) perspective view of a super pixel for full Stokes vector measurement with calculated time average TM power flow in the plane for Archimedean spirals and in a cross section for linear gratings.

Surface plasmons are possible when the real part of the dielectric constant is negative; they have lower Ohmic losses when the imaginary part is small, a condition satisfied in noble metals in an appropriate range of wavelengths. Silver generally has the lowest loss of any metal, but is difficult to work with because it corrodes easily. Gold tends to be favored
for plasmonic applications because the nearly inert surface makes it easy to work with and the loss is almost as low as silver in the IR. However, gold can only be used for deep red or IR wavelengths because of interband transitions in the green. There is one other aspect of the metal dielectric constant that is commonly overlooked, and that is its magnitude, particularly when trying to support a surface plasmon next to a dielectric other than air. Placing the metal near a higher index dielectric increases losses due to the lack of contrast between the metal and dielectric index of refraction. For instance, the propagation lengths of surface plasmons with silicon dioxide adjacent to different metals are shown in Figure 4.2. For the majority of the visible spectrum, aluminum is actually better than gold, and below about 550nm, it is even better than silver. In addition, the propagation length for surface plasmons at the aluminum-silicon dioxide interface is nearly constant in the visible as well, making it a much better candidate for a broad-band device. In our simulations, we use Al for designs operating in the visible (<700nm) and gold for longer wavelength designs.

![Figure 4.2: Calculated surface plasmon propagation length for different metals covered with SiO2.](image)

Finite element modeling of the electromagnetic response was carried out using COMSOL Multiphysics simulation software. Two-dimensional models were used to simulate infinitely long linear grating structures, with a mirror symmetry axis through the center of the aperture.
to reduce computation time. Full 3D models were used to simulate spiral structures. The models were truncated using perfectly matched layers\cite{25}, which minimize reflections from the outer edges of the geometry. While these reflections approach zero in 2D models, in three dimensions some small oscillations in our simulated transmission were sometimes observed due to residual reflections from the outer boundary of the model. Side wall slopes for the gratings and aperture were approximated using measurements of structures fabricated in our lab. Spectroscopic ellipsometry of fabricated structures was used to determine the optical constants and thickness of the deposited SiO$_2$, along with optical constants of the deposited gold for use in simulation. Optical constants for Al and Ag were taken from the literature. Because of memory constraints, an impedance boundary condition\cite{46} at the gold surface was imposed rather than simulating the fields inside the gold for the 3D models. This type of boundary condition accurately accounts for scattering losses and surface plasmon propagation along the surfaces, but forces direct transmission through the gold to be zero. The full field profile inside the metal was simulated in the 2D models. The time-averaged power flow (Poynting vector) was integrated just below the aperture to yield the magnitude of the power exiting the structure. For 2D simulations, the far-field electric field was calculated using the Stratton-Chu formula\cite{25} and then integrated over an angle appropriate to the collection angle of our measurement objective (NA = 0.5) for comparison to experimental data. Designs for linear polarizers with resonance wavelengths spanning the response of silicon detectors were developed using 2D models. Because of the long computation time in 3D (3-5 hours per data point), only a single resonance wavelength was simulated for circular polarizers.

While the design is relatively simple, there are in fact fifteen different material choices and geometric parameters required to define the linear structure. Many of these parameters are coupled in determining the optical performance of the micropolarizers. For instance, the choice of metal, dielectric index of refraction, and dielectric thickness determine the mode index of the surface plasmon slab waveguide. The mode index and grating periodicity deter-
mine the input coupling grating resonance wavelength. The grating groove depth determines the photon to plasmon coupling efficiency with deeper grooves having higher efficiency. However, the grooves also act as mirrors to surface plasmons with deeper grooves having higher reflectivity per groove. This leads to coupling between the groove depth and groove number, with the highest efficiency occurring for a small number of deep grooves.

Simple parameter variations are useful in understanding physical mechanisms and in determining which parameters are coupled, but this is a time-consuming approach for fully optimizing performance. We therefore implemented a Java-based automatic optimization routine using a gradient descent approach. The routine allows an arbitrary number of parameters to be simultaneously optimized to either maximize or minimize a given performance parameter, for instance to maximize TM transmission at a single wavelength. Each step of the optimization requires two calculations for each varied parameter to give a gradient centered at the current value. This makes the number of calculations $2n+1$ for each optimization step, where $n$ is the number of parameters to be optimized. In practice, optimization of four parameters for 2D simulations can be performed in a reasonable time frame. (The long computation time precluded automatic optimization of 3d structures.) Full device optimization typically proceeds in two or three steps starting from an initial guess obtained from simple parameter variation studies. In the first step, the grating period, groove depth, and dielectric thickness are optimized for a fixed number of grating grooves. This optimizes the vertical dimensions for input coupling of photons into surface plasmons. In the second step, the aperture width, cavity width, cap width, and grating periodicity are optimized. Grating periodicity is included again to ensure matching between the input grating resonance and the cavity resonance. A third step optimizes the location of an outer mirror when desired.

4.4 Measurement-Simulation comparison for linear micropolarizers

Samples were fabricated on polished microscope slides coated with 200-250nm of gold on top of a 2.5nm titanium adhesion layer. All patterning was done by electron beam lithography, with 50µm-long linear apertures fabricated in a first lithography level and gratings cut
into the metal layer using broad-beam argon ion milling in the second lithography level. The SiO$_2$ dielectric layer was deposited using plasma enhanced chemical vapor deposition. The metal cap covering the aperture was fabricated using a lift-off process in a third lithography level. Fabricated structures did not have the side mirrors shown in Figure 4.1a. Geometric parameters (grating period and depth, cavity width, aperture width and position, cap width and position) of the fabricated structures were measured using a combination of scanning electron microscopy and atomic force microscopy. More details on the fabrication have previously been reported[8]. Experimental far-field spectra were collected using an optical microscope configured for transmission measurements coupled to an Acton 300i spectrometer with a Princeton Instruments Spec-10:100BR liquid nitrogen cooled silicon CCD array detector. A fiber-coupled tungsten halogen lamp provided white light for an input arm that included divergence control lenses, wave plates, and high extinction ratio linear polarizers allowing the light incident on the sample to have any desired polarization state. Linearly polarized white light was incident on the air side of the structure and collected with a long working distance objective (N.A. = 0.5) after transmission through the polarizing element and 1mm thick glass substrate. The $\sim 24\mu m$ collection spot size was smaller than the $50\mu m$ pattern length and comparable to the pattern width. The collected light was focused onto the end of an optical fiber positioned in a conjugate relationship to the sample plane. The opposite end of the fiber was optically coupled to the entrance slit of the spectrometer. Raw spectra were background subtracted and normalized to a white light measurement made with no sample in place to yield absolute transmission data.

Structures were fabricated with 19 grooves in each of the two gratings with 500nm period and variable cavity width. The far-field transmission spectrum of a representative structure is shown in Figure 4.3a for TM polarization (example SEM images of the structure are shown in the inset). For this structure, 1.07% and 1.53% of the light incident on the entire structure was measured and simulated to be collected in the far-field, respectively. The measured and simulated far-field TM transmission show good agreement in terms of both peak location.
and *absolute* transmission efficiency. Both TM and TE spectra are shown in the semi-log plot of Figure 4.3b. The TE measurement is background limited for wavelengths longer than $\approx 600\text{nm}$. The extinction ratio, calculated from the measured TM and TE values has a lower limit of 3200. Using the measured TM and simulated TE signals provides an estimate of about 10,000 as the true extinction ratio that would be seen in an ideal measurement. Since the TE signal comes from direct transmission through the gold film, the extinction ratio can easily be increased by orders of magnitude simply by making the metal thicker. Attenuation of the TE signal as it propagates along the MIM waveguide to the aperture provides a separate limit on the extinction ratio that becomes important if the metal is sufficiently thick. The TE transmission through the aperture decreases exponentially with increasing cap width. Extinction ratios exceeding $10^{10}$ are predicted with reasonable values of metal thickness and cap width, as will be described in more detail below.

![Figure 4.3: (a) Absolute collected TM transmission for a structure with 19 grooves in each grating, but no outer mirror. The inset shows a representative SEM image of a complete structure and an off-angle detail of the central region. (b) TM and TE transmission of the same structure with a semi-log scale.](image)

4.5 High efficiency linear micropolarizers designs

In earlier work on a similar structure with no cap, we showed that the maximum transmission occurred when two effects that were controlled by the cavity width were optimized: 1) when there is constructive interference at the aperture between surface plasmons and
the incident plane wave, and 2) when successive reflections of the surface plasmon in the cavity form a Fabry-Perot resonance[5]. The cavity width provides a key design parameter for the structure with a cap as well. The simulated TM transmission for a few wavelengths is shown as a function of cavity width in Figure 4.4a. For all wavelengths, transition from minimum to maximum transmission (or vice versa) occurs when the cavity width increases by \(\sim 500\text{nm}\). Figure 4.4b shows the transmission as a function of wavelength for a few cavity widths. A large intensity variation is observed at the \(\sim 800\text{nm}\) design wavelength (the input grating was separately optimized for that wavelength). Adjacent transmission maxima are observed for cavity widths varying by approximately 1000nm. All of these simulations were performed with fixed cap width. The transmission decreases monotonically while varying the cap width with fixed gap between the cap and grating due simply to increased losses in the MIM waveguide. This shows the key parameter for this structure is actually the separation between the cap and the inner edge of each grating rather than the cavity width by itself. The maximum in transmission occurs when constructive interference between surface plasmons and the incident field maximize power coupling into the MIM waveguide at the edge of the cap. Increasing the cavity width by 1000nm increases the grating-cap separation by 500nm, equivalent to one plasmon wavelength for the free space wavelengths shown, as would be expected for adjacent interference extrema. We did not observe any noticeable cavity Fabry-Perot resonances, which we attribute to the fact that the presence of the cap improves guiding of light down into and out of the aperture. This damps Fabry-Perot resonant effects in the cavity.

The symmetric input gratings couple incident photons into surface plasmons traveling both toward and away from the aperture. Although all of the fabricated structures allow the power traveling away from the aperture to be lost, the automatic optimization routine was used to design visible wavelength structures with a terminating mirror to capture the component initially traveling away from the aperture. The mirror consists of a metal plug extending from the base metal through the dielectric into the air above, Figure 4.1. In terms
of fabrication, this would require an additional lithography step to remove the dielectric layer and fill it with metal. The horizontal position of the mirror relative to the grating has to be precisely controlled to ensure constructive interference between the reflected field and the field initially traveling toward the aperture. The optimum distance turns out to be approximately the free space wavelength divided by the mode index.

The side mirrors increase the transmitted power as expected, as seen in Figure 4.5. The transmission is calculated by dividing the transmitted power by the power incident on the total device area. For structures with no mirrors this area is taken as the outer edge of the input gratings, while structures with mirrors use the midpoint of the 500nm wide mirrors and hence have a larger area. The transmitted power therefore increases more than the figure suggests. For instance, the actual transmitted power for the 2-groove, 550nm model increases by a factor of 1.51 with the addition of the side mirrors while the normalized transmission efficiency in Figure 4.5 shows an increase of 8.8%. In addition to increasing the efficiency, the side mirrors substantially reduce the transmission bandwidth. The asymmetric peaks for the structures with no mirrors clearly come from multiple, overlapping resonances. Since the field reflected by the mirrors can only be exactly in phase for constructive interference at a single wavelength, transmission far from that value is suppressed. Note that substantially...
higher performance can be obtained at longer wavelengths using gold, as evidenced by the nearly 50% efficiency at 800nm shown above in Figure 4.5e.

Figure 4.5: Simulated absolute TM transmission for visible wavelength structures fabricated using aluminum (a-d) and gold (e). Peak wavelengths of 650, 550, and 450nm were selected to give red, green, and blue (RGB) filters. For each RGB set, vertical dimensions for the oxide thickness and groove depth were optimized for the green filter and held fixed for the red and blue filters to allow for simultaneous fabrication.

The skin depth of aluminum has a very small value at all visible and IR wavelengths, resulting in extremely low direct transmission in contrast to the fabricated Au layers discussed above. TE transmission is therefore determined by the attenuation along the MIM waveguide as light approaches the aperture. Initial modeling used a cap width of 450nm in order to minimize the loss due to light directly incident on the cap. The TM/TE extinction ratio had values around $10^4$ for most wavelengths, as can be seen in Figure 4.6a. While this value is substantially larger than has been demonstrated in alternate micropolarizer designs, the exponential decay of the cut-off TE modes in the MIM waveguide allow extremely high extinction ratios to be obtained. At 800nm wavelength, an MIM waveguide with 100nm dielectric thickness has a cut-off TE mode with a decay constant of 2.1418 corresponding to a propagation length (length in which power is decreased by a factor of $1/e$) of 30nm. Therefore, every 70nm of extra cap length gives an order of magnitude decrease in TE transmission.
through the MIM waveguide. In contrast, the TM propagation length for the same conditions is about 3.7 microns, roughly 1000 times that of the TE mode. Therefore, increasing the cap width to 1000nm increases the calculated extinction ratio to values around $10^8$ for wavelengths greater than 550nm with only a small decrease in TM transmission efficiency. The other method that can be employed is to decrease the oxide thickness. This cuts off the TE mode more rapidly, while only slightly increasing the TM losses. The extinction ratio at 400nm was found to be very sensitive to the SiO$_2$ thickness because the MIM waveguide does not cut-off the shorter wavelengths as strongly. For instance, reducing the 102nm oxide thickness used for the models of Figure 4.6b to 94nm increased the 400nm extinction ratio for the blue filter by nearly a factor of 30, the green filter by more than a factor of 10, and the already higher red filter by a factor of 5. Peak extinction ratios exceed $10^{10}$ for these designs. The two oxide thicknesses were obtained by optimizing the vertical dimensions (oxide thickness and grating groove depth) for 450nm or 550nm operation, with the shorter wavelength requiring a thinner oxide. Changing the oxide thickness had only a small impact on the TM transmission of the RGB filters.

![Figure 4.6](image)

**Figure 4.6:** Simulated extinction ratio for visible RGB filters with 2 grooves per side and cap widths of (a) 450nm and (b) 1000nm.

All of the modeling results presented above used normally incident light, but a focal plane array will see a range of incident angles dependent on the imaging optics of the camera. The impact of non-normal incidence was examined for an optimized 800nm structure with no
side mirrors. Two plane waves with incidence angles of $\pm \theta$ with respect to normal with $\theta$ varied from 0 to 20° were imposed on the structure. Simultaneously using both positive and negative incident angles simulates a focusing lens, and also maintains mirror symmetry about the center of the aperture allowing only half of the structure to be modeled. The simulated TM transmission as a function of $\theta$ is shown in Figure 4.7. The transmission efficiency drops by a factor of about 2.5 with little change in line width as the incidence angle increases to 4°. This angle corresponds to a lens with an f-number of about f6, a typical value for telephoto lenses. At 6° and larger, the transmission splits into two separate peaks but there is little additional change in efficiency. TE transmission is largely insensitive to incident angle, and hence extinction ratios demonstrate the same small change as is seen in the TM transmission.

Figure 4.7: Simulated TM transmission of a linear structure for a range of incidence angles.

4.6 Circular Micropolarizers

A design for circular micropolarizers using a pair of nested spirals analogous to radio frequency spiral antennas was examined and found to have good transmission efficiency and right/left circular extinction ratio. The design is essentially the same as the linear structures
with the grooves swept into a spiral around a circular aperture[45]. A key advantage of this spiral design is the ability to simultaneously fabricate both circular and linear sensitive structures with only horizontal geometry changes. Figure 4.8 shows the time-averaged power flow (Poynting vector) plots for one model optimized for a free space wavelength of 700nm for (a, c) right-circular (RC) and left-circular (LC) (b, d) light. We are using the convention where right-circular has the meaning that, in a plane perpendicular to the propagation, looking in the direction of propagation, the electric field rotates in the clockwise direction. The spiral configuration shown in Figure 4.8 effectively concentrates RC polarized light into the MIM waveguide created by the cap and then transports that energy out of the aperture. The field created in the aperture is essentially a rotating dipole which effectively radiates out of the aperture and into the far-field. For LC polarized light, the field is concentrated into a vortex that circles the aperture around and under the cap on the top surface, until the power is absorbed due to Ohmic losses. Therefore, this polarization does not effectively radiate. Interestingly, the grating efficiently couples both polarizations into the central cavity, where the magnitude of the Poynting vector for both exceeds 100 times its magnitude in the incident light.

The time-averaged power flow (Poynting vector) crossing a hemisphere just below the aperture was integrated to yield the magnitude of the power exiting the structure. Representative results are given in Figure 4.8e and f where the effect of changing the Archimedean spiral arm length is shown. All of the simulations showed a preference for RC transmission over LC. Note that inverting the handedness (the angular direction of increasing radius) would result in an LC-selecting element. As the spiral arm length increases, the grating more effectively couples RC light into the plasmon, increasing the transmission through the aperture and narrowing the bandwidth, which is expected for grating-coupled devices. For the different model arm lengths (measured as the angular distance traversed by each arm; $2\pi$ is one full rotation) varying from $1.425\pi$ to $4.5\pi$, the relative transmission integrated over all wavelengths increased from 31.3 to 79.6 times the power incident on the 200nm
Figure 4.8: Simulations of spiral gratings with circularly polarized incident light. The left column (a, c, e) has RC polarization and the right column (b, d, f) has LC polarization. The time average power flow at 700nm is shown in a-d with a color scale having dark red $= 0$ to white $\geq 50$ times the incident. Transmission spectra for four Archimedean and one logarithmic spiral structures are shown in e and f. The transmission through a bare aperture is also shown in e.
open aperture area. By contrast, the LC transmission showed little dependence on the spiral arm length, Figure 4.8f. For reference, we modeled a bare aperture in gold with no cap or SiO\textsubscript{2} coating, also plotted in Figure 4.8e, which confirmed that the spiral structure leads to strong transmission enhancement similar to what is observed with gratings in metal films with subwavelength apertures\cite{5}. While the absolute RC transmission increases as the number of turns increases, the active area efficiency (transmission normalized to the spiral area) actually decreases because the area of the structure increases faster than the transmission. The active area efficiency decreased with increasing arm length, from 13.70 to 8.58\%. This dependence on the number of grating grooves is consistent with results obtained with linear structures. Note that the only geometric parameter varied in this study was the spiral arm length, so substantial improvements in efficiency are likely with additional optimization.

One feature of this structure is that it has the ability to filter color simultaneously with polarization. The bandwidth of the structure can be controlled, and both narrow-band and wide-band filters have their own applications. Longer spirals are desirable for narrow-band applications. For broad-band applications, shorter arm lengths or a different kind of spiral may be used. Figure 4.8e also shows the simulated transmission through a logarithmic spiral where the radius of the spiral varies exponentially with angle, as shown in the inset of Figure 4.8f. A substantial increase in transmission bandwidth is observed.

Figure 4.9a shows a comparison between the 4.2\(\pi\) simulation of Figure 4.8e and the far-field transmission measurement for a fabricated structure having the closest geometric match. Good agreement is obtained for RC polarization between the main peak around 700\text{nm} as well as a secondary peak around 975\text{nm}. The measured main peak width is smaller than the simulation, possibly because of the geometric differences between the model and fabricated structures. The inset shows an overlay of the 4.2\(\pi\) model spiral image on the SEM image of one structure, providing a visual representation of the geometric differences. Smaller measured peak widths are also seen in comparing structures with 3\(\pi\)-turn spirals. For LC polarization, the measurement and simulation have similar amplitudes but different
peak locations. The wavelength integrated right/left circular extinction ratio was 5.1 for the measurement, quite close to the 5.65 value for the model. Measurements on structures with different cavity widths show little variation in peak position and amplitude for RC polarization, Figure 4.9b, but a strong dependence for LC polarization, Figure 4.9c, leading us to attribute the LC differences in Figure 4.9a to the geometric differences. We experimentally found that, for $4\pi$ structures, the right/left extinction ratio generally decreased, from 8.3 to 5.1, with increasing cavity width due to higher LC transmission.

![Figure 4.9](image)

Figure 4.9: (a) Comparison of simulated transmission with measured transmission through the structure with the closest geometrical match. The inset overlays the modeled geometry on the SEM image of the measured structure. Measured transmission for different cavity widths is shown for (b) right circular illumination and (c) left circular illumination.

### 4.7 Photodiode Integration

A major advantage of our technology is the potential for monolithic integration of the plasmonic structures on a CMOS photodiode focal plane array. The plasmonic structure can be fabricated directly into the Ohmic contact metallization of the diode, completely eliminating the possibility of optical crosstalk due to the polarizing filters. Since transmission is limited to the subwavelength dimension aperture, the active area of the diode can be reduced allowing higher speed, lower noise diodes to be used. For testing purposes, an array of 48 mesa diodes (4 rows of 12 diodes) with contact leads going out to the perimeter of a 1cm² chip was fabricated. Diodes were fabricated on 5-10Ω-cm p-type Si wafers with the junction formed by PECVD growth of 500Å intrinsic a-Si:H followed by 500Å n-type a-Si:H. This was followed by blanket evaporation of 200Å Ni and 2500Å Au. The Ni acts as both
an adhesion layer and as the Ohmic contact to the n-type a-Si:H. Broad-beam Ar ion milling defined the 100\(\mu\)m x 300\(\mu\)m mesa diode area. This was followed by blanket PECVD growth of 1000Å SiO\(_2\) to passivate the diode side walls and electrically isolate the exposed c-Si of the wafer. A 100\(\mu\)m x 100\(\mu\)m via at one end of the diode provided an open field for e-beam lithography of the micropolarizers, while an 80\(\mu\)m x 80\(\mu\)m via at the other end provided contact area for the probe leads formed by evaporation of 25Å Ti and 2000Å Au followed by lift-off. A full Stokes vector polarimeter was fabricated using three linear orientations (0, 90, -45) plus a spiral array in groups of four diodes, forming a sub-pixel arranged in a 4x3 array as shown in Figure 4.10a.

For optical measurements, a mechanical chopper was placed in the illumination path to provide a reference frequency for a lock-in amplifier. The device under test was mechanically probed and directly connected to the current input of the lock-in, resulting in a short circuit current measurement of the chopped light. The illumination spot size was restricted to a diameter below 100\(\mu\)m allowing the full spot to remain on the diode metal. To measure the linear response of our micro-polarimeter, we illuminated the device through the microscope while controlling the polarization state of the light. Unfortunately, the microscope optics was heavily birefringent, which precluded the ability to control the polarization state reliably before entering the microscope. Therefore, we constructed a small linear polarizer that could be placed between the objective and the sample and could be rotated to achieve a reliable linear polarization state. This however, could not be used to control circular polarization states, and a more complicated solution would need to be devised to measure the circular polarization selectivity of the structure. Figure 4.10b shows the detected signal for one sub-pixel as a function of the angle of the incident linearly polarized light. The response is exactly the expected behavior of the polarimeter. The difference in relative size of the signals and the noise in the signal is attributed to variations in the positioning of the illumination spot as the polarization is rotated, which increases or decreases scattering around the edges of the metal pads. Again, this can be eliminated by an array design that has light shields in
place between the pixels. This demonstrates the utility of the structure as a micropolarimeter that is compatible with fabrication directly on detector arrays. The non-zero minimum signal comes from scattered light hitting the bare silicon around the diode metal, and generated electrons diffusing to the junction.

![Figure 4.10: (a) Optical and off-angle SEM images of an active polarimeter array; (b) photodiode response versus incident linear polarization angle.](image)

4.8 Conclusions

This program has demonstrated grating coupled plasmonic waveguide structures with linear polarization sensitivity of at least 3200, a value believed to be measurement limited. Structures with this performance can be routinely fabricated using a process with three lithography levels. Finite element modeling of these structures predicts a wavelength integrated TM/TE extinction ratio over $10^6$ with peak values over $10^{10}$. The wavelength performance can be tuned from a single narrow band to broad multiple bands by adjusting the grating parameters, with transmission efficiency as high as 50% for the broad-band designs. In addition to ultra-high linear extinction ratios, spiral gratings provide direct circular sensitivity in a plasmonic structure. This allows all polarization components to be measured using structures fabricated in three common lithography steps, providing a solid base for the development of a full Stokes vector polarimeter-on-a-chip focal plane array. A small 4x3 diode array able to measure the full Stokes vector was fabricated and shown to have good...
performance.

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CHAPTER 5
CONCLUSIONS

In this thesis, experimental results regarding nanostructured polarizers were discussed. A brief motivation was presented, indicating their viability for high extinction ratios and spatial focusing which would make them ideal for CCD integration. The performance of one such linear polarizing element was tested, and it was found to produce extremely high extinction ratios, along with a transmission profile that agrees well with simulated predictions. These structures were then fabricated directly onto silicon diodes and their photoresponse was tested, also confirming predicted performance.

Close pairing between experiment and simulation can provide key guidance leading to the improvement of both approaches - simulation allows for exploring large parameter spaces with little cost. Measurement is necessary to confirm simulation, and to give feedback on where simulation fails and is therefore unfit for designing structures. Essential to this pairing is a good understanding of the implicit assumptions of both simulated and experimental systems, and verification that the actual results hold to these assumptions.

On the experimental side, assumptions used in the simulation must be imposed using experimental controls. For example, one assumption was light being measured at the spectrometer was the signal from the sample, and that the signal from the sample was in fact due to the structure; this was tested using null samples to detect and eliminate stray signal. Of course, there were limits to our ability to eliminate all stray signal, be it light leaking through alignment marks put in place during the fabrication, or direct transmission through the gold films having a nonzero contribution to the signal. Knowing the background limits aided in analysis of data.

Simulation is always in some way an idealization: symmetry, sharp corners, perfectly straight edges, and metals which are perfect conductors below a certain depth were chosen to facilitate efficient computation. However, as much care as possible was taken to make the
simulated structures close to what would be measured, and in most cases good quantitative agreement was reached. It is important to account for the sloped walls present in fabricated gratings. Simulations show that the sloped-wall gratings have resonances which are slightly detuned from that of a perpendicular-walled grating of the same period, which should be accounted for when designing for a target resonance. Simulated sharp corners gave rise to high fields, which are probably non-physical because real structures are rounded during fabrication. The integrated results presented from simulations were largely unaffected by these high fields due to the localized nature of high fields at the corners.

The transmission through unpatterned gold films was fully simulated and characterized for comparison with experimental measurements. In fact, the measured signal from structures was often characterized as a sum of the structure transmission and the direct transmission of the surrounding gold. This direct transmission was found to be significant for low wavelengths (where gold transmits more light) and for TE transmission (where direct gold transmission dominated over TE transmission through the aperture). For TM measurements, direct transmission was negligible near the design wavelength of the structure.

Simulations treating asymmetries in fabricated structures found that if the aperture is far enough off center, the device does not launch a beam of light propagating away from the surface, but instead couples to a surface plasmon along the bottom of the gold surface traveling to one side. This effect was not fully studied, and was never measured experimentally, but appears to rely on interference between the plasmons traveling into the aperture from either side. Such directional coupling has possible applications in optical computing.

The transmission through the spiral structures also bears future investigation. Based on the results of the 3D simulations, the spiral structures pass little of the light of their intended blocked polarization due to coupling into a plasmon vortex field, which is trapped at the surface. The passed polarization couples into a rotating dipole in the aperture. The interesting behavior is that the dipole rotates so as to emit an opposite circular polarization - a spiral that only transmits when illuminated with right circular light transmits left circular light.
through the aperture. Arrays of these structures could form an interesting metamaterial.

The measurement apparatus has many areas which could be substantially improved with regard to reliability and efficiency. Of greatest note are the adaptations intended to create a planar illumination spot. For applications where that is not essential, the long arm length, and associated alignment difficulties could be foregone.

All of the light controls present for use with white light could also be adapted for use with a laser source. By transitioning from a white light source to a tunable frequency laser coupled to a single mode illumination fiber, the same apparatus could be used, and the increased power would allow for much higher extinction ratio measurements, provided that the optics (especially the polarizers) can deal with the incident power.

The apparatus can also be utilized to give extremely localized transmission measurements for material property assessment (such as on microscopic defects), and to characterize this transmission function of polarization state. Theoretically, by controlling polarization on both the collection and illumination channels, the birefringence of a sample could be measured as a function of wavelength with micron level spatial precision.
CHAPTER 6
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