Simulation of practical single-pixel wire-grid polarizers for superpixel stokes vector imaging arrays

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Abstract. An optical tracking sensor that produces images containing the state of polarization of each pixel can be implemented using individual wire-grid micropolarizers on each detector element of a solid-state focal plane array. These sensors can significantly improve identification and tracking of various man-made targets in cluttered, dynamic scenes such as urban and suburban environments. We present electromagnetic simulation results for wire-grid polarizers that can be fabricated on standard imaging arrays at three different technology nodes (an 80-, 250-, and 500-nm pitch) for use in polarization-sensitive detector arrays. The degradation in polarization performance with the larger pitch grids is quantified. We also present results suggesting the performance degradation is not significant enough to affect performance in a man-made vehicle-tracking application. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.1.016201]

Subject terms: hyperspectral imaging; polarimetry; polarizers; hybrid imaging arrays.

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1 Introduction

Optically locating and following a moving target through a cluttered environment is a challenging task. Target detection and tracking can be made much more robust by exploiting specific signatures of an artificial target relative to a natural background, such as spectral characteristics (via multispectral or hyperspectral imaging) or polarization state. For a single linear polarizing element in the input optics of a detector system, there are 2 possible angles of polarization. This can be obtained by rotating the complete Stokes vector describing the polarization state of each pixel in an image, but this is only practical for slow-moving or static scenes. For rapid data collection of fast-moving scenes at video rates, the Stokes vector of the entire scene must be collected coincidentally. This can be accomplished by simultaneously collecting three polarization images for each pixel at 0, 60, and 120 deg linear polarization, for example. These polarimetric images may be produced by imaging a scene with multiple cameras, each with a suitable polarizer in the input optics, but this process can be complicated by the need to accurately register each camera relative to the others. A more robust solution may be obtained by permanently integrating the polarizer or polarizer array with the imaging detector in a hybridized configuration. The Full Stokes vector can be obtained with this approach by segmenting the polarizer plus imager array into superpixels composed of 2 × 2 pixels, each with a linear polarizer element at a different angle, as illustrated in Fig. 1(a). This proposed array contains superpixels with individually polarized elements at 0, 60, and 120 deg linear polarization, plus a single unpolarized pixel element. These arrays can be fabricated by affixing an array of wire-grid polarizer elements on an optical element to the imaging array. An alternative approach proposed here avoids introducing another set of optical surfaces and avoids the challenge of aligning and securing the polarizer array on the imaging array by fabricating a set of pixel-sized wire-grid polarizer elements directly on each element of the imaging array. If there is sufficient demand for these devices it is straightforward to fabricate these hybridized arrays during the microfabrication process, but for low-volume and research purposes it may be necessary to create the polarizer arrays on an unpackaged commercial imagers.

Some authors have already reported successful integration of pixel-sized polarizer arrays on optical detectors using aluminum wire grids fabricated with electron-beam lithography. Very-high-efficiency micropolarizer elements can be fabricated using the fine linewidths achievable with e-beam lithography processes. Unfortunately, this process is expensive, low throughput, and can potentially degrade optical detectors via radiation damage effects. Low-impact optical or nanoimprint lithography can produce a suitable grid pattern on each pixel of an imaging array, but the linewidths and spacing produced will be wider than that achievable by an electron-beam lithography process. The advantage is that the more conventional optical lithography processes will have much higher throughput and be much cheaper.

The study of lower-cost fabrication processes was part of an effort looking at MEMS-based adaptive sensors for urban surveillance applications. Simulation of imaging systems and target tracking algorithms using the Rochester Institute of Technology (RIT)’s digital imaging and remote-sensing image generation (DIRSIG) model was used to investigate whether target-detection probability and tracking-path accuracy can be significantly improved by using polarimetric imaging with even relatively low-efficiency large-spacing polarizer elements. Detailed optical performance parameters for these low-efficiency polarizing elements were unavailable in the literature, so we selected three example technology nodes that could realistically produce integrated or add-on single-pixel polarizer elements without destroying an existing imaging detector array. We simulated polarizer elements at a 500-nm pitch (readily fabricated using high-NA i-line or...
deep-UV optical lithography), a 250-nm pitch (fabricated using advanced deep-UV optical lithography), and an 80-nm pitch (achievable using advanced nanoimprint or state-of-the-art immersion optical lithographic processes). The simulated optical throughput of these devices was then used to postprocess hyperspectral polarization-resolved DIRSIG video simulations in Mathworks Corporation (Natick, MA, USA) MATLAB analysis software to assess the ability of a tracking algorithm to monitor the position of a number of moving vehicular targets in a simulated cluttered urban scene.

This paper describes the geometry and electromagnetic wave propagation modeling of the wire-grid polarizers, the resulting polarization performance, and the impact of that performance on the vehicle-tracking application.

2 Geometry and Analysis

Wire-grid polarizer arrays were simulated using COMSOL Multiphysics (COMSOL Inc., Burlington, MA) finite element modeling software release 3.5a using the two-dimensional (2-D) in-plane hybrid electromagnetic wave application mode of the radio frequency (RF) modeling module. Three different wire-grid geometries were modeled as described in Table 1.

<table>
<thead>
<tr>
<th>Pitch (nm)</th>
<th>Linewidth (nm)</th>
<th>Gap spacing (nm)</th>
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A relatively coarse 500-nm-period grid with 100-nm-wide lines 100 nm thick was simulated as a geometry that could be fabricated in our microelectronics lab on high-NA i-line lithography equipment with a moderate amount of effort. A more aggressive 250-nm-pitch grid, which would require more complex and expensive deep ultraviolet lithographic techniques was simulated. An 80-nm-period grid with 20-nm lines 20 nm thick was chosen as a candidate geometry that we could fabricate using more aggressive immersion lithographic techniques.

The metal grid was specified to be aluminum with $35.6 \times 10^6$ siemens/meter conductivity with a center aperture of 10 $\mu$m. Literature values for the complex permittivity of aluminum in the visible region were interpolated and extrapolated to the near infrared and entered into the COMSOL model as a wavelength-dependent function. The modeling space was defined as 10 $\mu$m total perpendicular to the centered grid, and 15 $\mu$m in the plane of the grid, with a solid metal aperture plate bounding the vertical central 10-$\mu$m grid opening of a detector with a 17-$\mu$m element pitch, as shown in Fig. 1. The wire-grid model is infinite in extent in the direction perpendicular to the plane of the figure. A 1-$\mu$m-thick perfectly matched layer (PML) was defined surrounding the modeling space, and scattering boundary conditions were defined at the outer boundary.

Electromagnetic plane waves were excited at the leftmost boundary of the modeling space before the PML, and transmitted electromagnetic power was extracted by integration of the Poynting vector at the rightmost boundary after the wave had propagated through the metal grid. The relative intensity of in-plane and perpendicular-to-plane electric and magnetic fields of the incident plane wave was specified to produce the polarization condition desired. That is, the electric field ($E$) was defined as entirely out-of-plane for the s-polarized (90-deg angle of polarization) case, and the electric field ($E$) was defined as entirely in-plane for the p-polarized (0-deg angle of polarization) case. The in- and out-of-plane incident fields were thus defined as $E_{\text{in}} = E_0 \cos \theta$ and $E_{\text{out}} = E_0 \sin \theta$, respectively, where $\theta$ is the polarization angle between the incident electric field and the orientation of the wire-grid array.

Meshing of the modeling space was refined until the solution obtained converged and was essentially unaffected by further refinement. Simulations were performed by parametrically stepping through wavelengths from 400 to 2500 nm by 10-nm increments. The simplified model described here does not fully account for detailed effects such as polarizer
edge termination,\textsuperscript{11} the gap between polarizer and detector,\textsuperscript{12} and diffractive effects from the 2-D frame around the polarizer. However, the model provides good qualitative agreement with more sophisticated approaches using finite-difference time domain methods while remaining computationally simple enough to provide polarizer performance metrics across a broad range of input wavelengths. Patterning of a wire-grid polarizer array directly on a detector surface is also expected to potentially excite near-field effects\textsuperscript{13} that may produce wavelength-dependent enhancements or suppressions of both s- and p-polarized radiation, leading to narrow peaks and valleys in the extinction ratio observed for a given polarizer. These effects are neglected in this model, but might be utilized to improve device performance in specific spectral regions of interest in future work.

3 Polarization Performance Results

Figure 2 describes the simulated raw-transmission characteristics on a log scale of the three wire-polarizer geometries selected in the wavelength range 400 to 2500 nm, plotted for linear polarization angles from 0 to 90 deg. Transmission is defined in this case by simply taking the ratio of transmitted electromagnetic power integrated across the right boundary divided by the incident power integrated across the left boundary. Results for the 80-nm-pitch polarizer grid show better than $-20$ dB attenuation of s-polarized light throughout the range 450 to 2500 nm, in qualitative agreement with comparable wire-grid polarizer simulations using other modeling techniques.\textsuperscript{11,12,14} Maximum transmission of p-polarized light is approximately 0.7 across the full wavelength range 400 to 2500 nm. Wire-grid polarizers of 250 nm attain better than $-20$ dB attenuation of s-polarized light only for wavelengths 1300 to 2500 nm and at least $-10$ dB attenuation down to 600 nm, with performance decreasing rapidly at shorter wavelengths. In comparison, 500-nm wire-grid polarizers have relatively poor attenuation performance of s-polarized light at all wavelengths studied, with $-10$ dB attenuation or more only at wavelengths greater than 1300 nm. The 500-nm polarizer becomes ineffective as the incoming wavelength approaches the pitch of the polarizer. Detailed behavior of the 500-nm polarizer in the 400- to 500-nm wavelength range is sensitive to the size and shape of the individual wires making up the polarizer.

Extinction ratios of the simulated polarizers can be calculated by taking the ratio of transmission at 0 deg polarization to the transmission at 90 deg polarization. This represents the relative intensities of p-polarized to s-polarized light from a randomly polarized input transmitted through the polarizer.

$$r_e(\lambda) = \frac{\tau_{\max}(\lambda, 0 \deg)}{\tau_{\max}(\lambda, 0 \deg)} = \frac{\tau(\lambda, 0 \deg)}{\tau(\lambda, 90 \deg)}.$$  \hspace{1cm} (1)

Extinction ratios for all three polarizers simulated are plotted in Fig. 3 on a log scale as a function of wavelength. For comparison, commercial macroscopic calcite and nanoparticle polarizers are available with extinction ratios exceeding $10^5$, and commercial infrared wire-grid polarizers are available with extinction ratios exceeding $10^2$. The simulated 80-nm wire-grid polarizer provides an extinction ratio...
greater than $10^2$ for all wavelengths 500 to 2500 nm, while the 250-nm wire-grid extinction ratio only exceeds $10^2$ above 1600 nm, and exceeds $10^3$ for wavelengths longer than 650 nm. The 500-nm wire-grid extinction ratio is relatively poor at all wavelengths investigated, exceeding $10^3$ only for wavelengths above 1500 nm and rapidly dropping to unity (i.e., no polarization contrast) at shorter wavelengths approaching 500 nm.

Finally, the diattenuation response of a polarizer is a measure of the polarizer efficiency, defined as

$$D(\lambda) = \frac{\tau_{\text{max}}(\lambda, \theta) - \tau_{\text{min}}(\lambda, \theta)}{\tau_{\text{max}}(\lambda, \theta) + \tau_{\text{min}}(\lambda, \theta)} = \frac{\tau(\lambda, 0 \; \text{deg}) - \tau(\lambda, 90 \; \text{deg})}{\tau(\lambda, 0 \; \text{deg}) + \tau(\lambda, 90 \; \text{deg})}. \tag{2}$$

Ideally, the diattenuation response of a polarizer will be relatively flat over the wavelength range of interest, with a value close to unity. The diattenuation response of all three simulated wire-grid polarizers is plotted in Fig. 4 as a function of wavelength. The 80-nm-pitch wire-grid polarizers produce a relatively flat diattenuation response greater than 95% throughout the wavelength range 400 to 2500 nm, while the 250-nm polarizer achieves this level of diattenuation only at wavelengths longer than 1000 nm, with a rapid decrease in performance at shorter wavelengths to a minimum of 0.18 at 400 nm. The 500-nm polarizer grids exhibit relatively poor diattenuation throughout the wavelength range studied, with a maximum diattenuation of 0.94 at 2500 nm rapidly decreasing to zero at 500 nm.

For each simulated wavelength, spectral video imagery from DIRSIG was processed with the polarizer transmission results to simulate the output from the 2 x 2-superpixel Stokes vector detector [assuming a constant detector signal-to-noise ratio (SNR) of 200], and the processed video was input to Numerica’s algorithm simulator for tracking and observations (ALTO), a hyperspectral target tracking algorithm to assess target detection and tracking performance. The ALTO algorithm with video-processing examples is described fully elsewhere. It employs measurement of target features (e.g., spectral radiance, polarization state) to aid in identifying, classifying, and distinguishing between multiple targets. Two of the key metrics associated with the ALTO tracking algorithm are track completeness, which is a normalized measure of the probability of correctly identifying a moving target vehicle, and Track Purity, which is a normalized measure of how long a track retains the correct vehicle without losing the target (due to clutter, for example) or incorrectly switching to a different nearby vehicle. Perfect tracking performance gives a unity track completeness and Track Purity measure. Track completeness is defined as

$$\text{Track Completeness} = \frac{\text{of Valid-Tracks}}{\text{of Should-Tracks}}. \tag{4}$$

Valid-Tracks are defined as detected targets that are confirmed to be within a 4-m radial distance to its known position output by SUMO, while Should-Tracks is the total number of targets that have been placed in the field of view. This parameter can also be described as the “probability of target detection,” which is a primary figure of merit for any target-tracking algorithm. The Track Purity parameter is defined as

$$\text{Track Purity} = \frac{\text{of epochs a valid tracks followed the same truth vehicle}}{\text{total of epochs in a valid track}}. \tag{5}$$
Track Purity is a measure of how accurately the tracking algorithm can follow a target when it is occluded by an object, such as an overhanging tree, or when it encounters an ambiguous situation, such as two targets meeting at an intersection. If the predicted target track jumps between two closely spaced vehicles, or fails to positively reacquire a previously tracked target after an occlusion, it reduces the Track Purity parameter. Table 2 illustrates some of the initial tracking results for two video sets that were generated for both the 80-nm polarizer and the 500-nm polarizer models. It should be noted that addition of polarization dependence does not improve tracking performance in all simulations over plain panchromatic tracking simulations, especially in the presence of atmospheric haze and other interference. Also, in general, simulations of the 80-nm polarizer sensors are superior to those generated by 500-nm polarizer sensors. This data set consisted of 151 frames at 10 Hz simulated for a 50-deg oblique viewing angle with 1120 × 1760 pixels and 13 spectral bands from 400 to 2500 nm and four Stokes bands, with 32 vehicles to track. It is interesting to note that tracking metrics for the 500-nm polarizer were comparable to those obtained for the 80-nm polarizer, implying that at least for some conditions of target, illumination, clutter, and atmospherics, the low-performance polarizer elements provide sufficient contrast in the near infrared to be effective in improving target tracking in cluttered urban environments. Also interesting is the higher Track Purity metric for the 500-nm polarizer sensor compared with the 80-nm polarizer sensor. The ALTO target-tracking algorithm uses the spectral and polarization signature of a target to distinguish it from other nearby targets. This signature can vary as a target moves into different illumination conditions or changes direction, so ALTO has to compensate for this changing target profile without misidentifying an altered target as a completely new target. Although both the 80- and 500-nm polarizer arrays provide for improved target detection, we believe that in at least this case the higher performance of the 80-nm polarizers produces a large enough change in target signature to confuse the tracking algorithm for some tracks, while the lower-performance 500-nm polarizer sensor do not produce sufficient change in the target signature under the same motion and illumination conditions to break the target-tracking lock.

5 Conclusions

Optical performance metrics for three single-pixel wire-grid polarizer elements using three fabrication technology nodes are described. As anticipated, a wire-grid polarizer fabricated with an 80-nm pitch provides good diattenuation and extinction ratio performance across the design wavelength range 400 to 2500 nm. Wire-grid polarizers fabricated with low-cost technology at a 500-nm pitch provide relatively poor optical performance in terms of diattenuation and extinction ratio, but are shown to still enable good target-tracking capability in urban scenes under specific circumstances. These results offer the potential of fabricating highly integrated Stokes vector detectors at relatively low cost and high volume using moderate resolution microlithography.

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References


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