Metasurface Dichroic Mirrors and Applications to Solar Energy via Spectral Splitting

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Abstract:

Multi-junction solar cells are the current leaders in efficiency since they reduce thermal losses by employing series-connected sub-cells with different bandgap energies. However, they are costly to produce and limited by current matching, because each solar cell is connected in series with one another. One alternative is to simply split light into ideal bandwidths and tailor separate photovoltaic modules to each bandwidth. Conventional dichroic mirrors can selectively split light by reflecting certain bandwidths while transmitting others. However, these mirrors do not operate well under different angles of incidence, which is critical for concentrated photovoltaics. Simulations show that metasurface structures can achieve similar characteristics to those of conventional dichroic mirrors while remaining resilient to the angle of incidence (AoI). Two such structures were created using electron beam lithography and were subject to transmittance testing. We proposed a low-loss, AoI-resilient single-layer metasurface dichroic mirror that could split light into ideal bandwidths for such a solar module. Simulation and experimental data show promising results, however, a multi-layer structure may be more ideal.

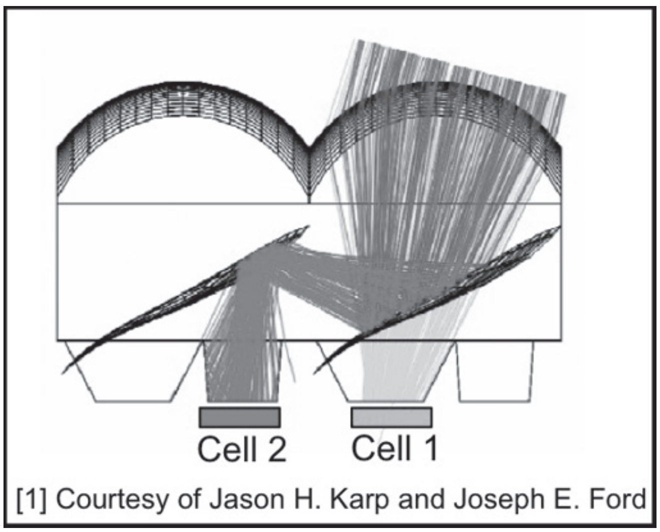

Figure 1: Possible solar concentrator apparatus that depicts both the concentration and splitting of light.

Introduction:

Multi-junction solar cells are highly efficient (max around 43.5%), but they are quite costly and limited by current matching since each sub-cell is connected in series. Alternatively, dichroic mirrors could be used to split light into different bandwidths and separate photovoltaic modules could collect energy specific to each bandwidth. Figure 1 shows a sample apparatus that could be used to split incoming light into separate bandwidths for concentrated solar energy collection.

Conventional dichroic mirrors can split light into separate bandwidths. However, these mirrors do not operate well under non-normal incident angles. When using concentrated photovoltaics, the AoI of light constantly varies due to the high concentration. Simulations show that metasurface dichroic mirrors have characteristics similar to those of conventional dichroic mirrors while remaining resistant to the AoI.

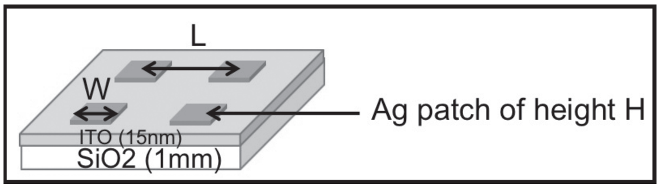

Figure 2: Idealized periodic section of the metasurfaces that were simulated and constructed.

Experimental Procedure:

After extensive simulations of a single-layer structure using RSoft DiffractMOD, as depicted in Figure 2, we decided to create two structures. Structure 1 was defined by W = 100 nanometers (nm), L = 200 nm, and H = 40 nm. Structure 2 by W = 200 nm, L = 400 nm, and H = 40 nm. The structures were created in four steps: (1) Coating the substrate (1 mm SiO_2 with 15 nm ITO on top) with positive resist, (2) Using electron beam lithography to design the patterns and developing the sample, (3) Using electron beam evaporation to deposit 2 nm of Ge (adhesion layer) and then 40 nm of Ag on the sample, and (4) Lift-off of the excess deposition.

The structures were then tested using a device that consisted of a light source, a diffraction grating, a monochromator to select a specific wavelength of light, and a detector. The light was first shone (under TM polarization) through an empty hole to the detector. This calibration data was recorded, and then the sample was placed on the sample holder such that light could shine through it. By comparing the initial light that passed through empty space to that which passed through the sample, we calculated the transmittance of our samples. Additionally, the sample holder could rotate, allowing for calculations at different AoI.

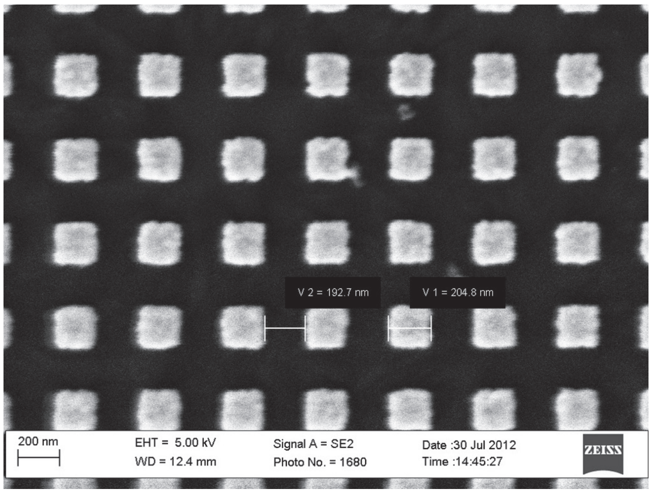

Figure 3: SEM image of the 200 nm structure.

Results and Conclusions:

Both samples were successfully fabricated. Figure 3 shows a close up of the 200 nm structure, with measurement bars. However, after thorough testing, the samples became damaged, and the subsequent data collection began to deteriorate in accuracy. Regardless, useful data was collected.

Figure 4 depicts the transmittance graphs for the experiments using the 100 nm structure. All data was collected under TM polarization. Dichroic mirrors were relatively sensitive to the AoI. Their transmittance dip (or reflectance peak) significantly shifted as the AoI increased. The simulations and experiments with the 100 nm structure showed a transmittance dip that was resilient to the AoI. However, the actual trend did redshift a bit more than predicted, and the dip was not as strong as predicted. This was probably due to sample damage, as this sample tended to somewhat rub off while testing. Regardless, the structure remained more resilient to the AoI than conventional dichroic mirrors.

Future Work:

Multi-layer structures may be more ideal for such a spectral splitting apparatus. In [2], the double-layer structure studied has a transmittance dip with a wider bandwidth dip, which is more similar to the conventional dichroic mirror. Furthermore, this structure was resistant to the AoI up to about 40°. By using metasurface dichroic mirrors, according to [3], a concentrated solar module with four mirrors and five photovoltaic collectors may have an estimated efficiency around 43%.

Acknowledgments:

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[1] J. H. Karp and J. E. Ford; "Multiband Solar Concentrator Using Transmissive Dichroic Beamsplitting," Proc. SPIE 7043, 70430F1-8 (2008).

[2] Li, Ping-Chun, and Edward T. Yu. "Wide-Angle Wavelength-Selective Multilayer Optical Metasurfaces Robust to Interlayer Misalignment." Unpublished Data (2012).

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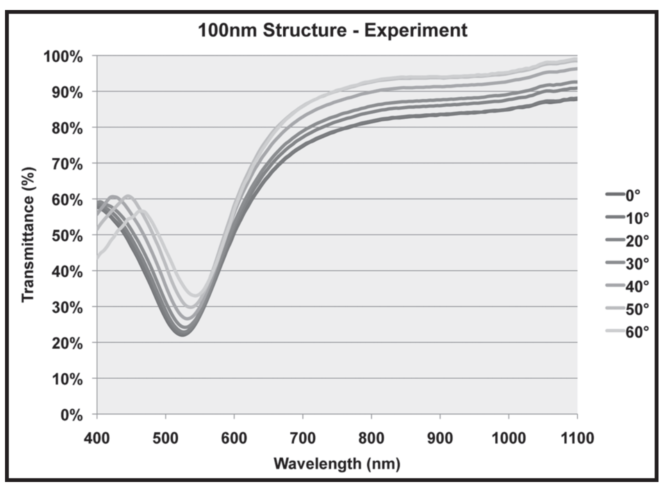

Figure 4: Graph of the 100 nm experiment structure depicting the resilience of the transmittance dip to the AoI.