User's Guide

DMD Diffraction Efficiency Calculator

TEXAS INSTRUMENTS

Abstract

The DMD Diffraction Efficiency Calculator is utilized for modeling diffraction energy in a system with defined input and output optical parameters which results in DMD diffraction patterns and diffraction efficiency. The underlying calculations implement non-paraxial scalar diffraction theory to simulate DMD diffractive effects. The calculator is implemented utilizing a user-friendly MATLAB GUI in which the user can enter DMD parameters for specific optical and wavelength designs which helps generate customized results. The GUI simplifies diffraction modeling for the user as the user only needs to provide specific DMD optical and wavelength designs parameters. Understanding and designing for diffraction efficiency can lead to improved system performance.

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1 DMD Diffraction Efficiency Calculator Functionality

The MATLAB code behind the calculator for computing DMD diffraction patterns and the optical design efficiency utilizes non-paraxial scalar diffraction theory as demonstrated by Dr. James Harvey [1]. This method approximates more rigorous Electro Magnetic (EM) methods and has shown good agreement with measurements. For longer wavelengths that approach the mirror size, the accuracy is reduced and more rigorous methods can be required [1]. This model is important to use when designing DMD based optical systems to correctly account for diffractive effects.

Note

As the wavelength approaches the order of the mirror size, the accuracy of the model decrease.

The user enters key DMD and optical parameters which are then converted to direction cosines in Fourier transform space. The method iterates through the illumination cone angle and launches plane waves from each discrete sample location. DMD's behave similarly to a 2D blazed diffraction grating. As the plane waves interact with the DMD, a range of diffraction orders are generated as each wave interaction occurs. The magnitude of the Fourier transform squared is then taken and the resulting diffraction pattern is stored for each incident wave. The model incoherently integrates over wavelength and source extent. The diffraction efficiency is calculated from the fractional power that falls within the projection lens aperture. The ratio of the output versus the input optical power is considered the diffraction efficiency.

Note

Please see DLPA037 for more information regarding DLP DMD diffraction efficiency.

Once the application has completed each calculation, a variety of outputs are displayed. The diffraction pattern in 2D and 3D are displayed along with a diffraction efficiency plot. An excel file is created with stored diffraction efficiency values across the wavelength spectrum. The average diffraction efficiency is shown and weighted against the photopic curve where the output is then recorded as the photopic diffraction efficiency. The diffraction pattern energy distribution can be saved to an excel file if the user selects the “Save Diffraction Pattern Data?” checkbox.

2 Installation and setup

This application was built in MATLAB and then converted to a standalone executable file utilizing MATLAB Runtime. **A MATLAB license is not required**. Install MATLAB Runtime by navigating to https://www.mathworks.com/products/compiler/mathlab-runtime.html. Once there, download the R2024a (24.1) version of MATLAB Runtime. After downloading this version of MATLAB runtime, install MATLAB Runtime by navigating to and selecting the setup.exe file from the downloaded folder.

Once this is complete, the user can open and run the application by select the "DMD Diffraction Efficiency Calculator vx.exe" file. The “photopic.txt” file needs to be in the same directory as the Diffraction Efficiency Calculator for the application to calculate the Photopic Diffraction Efficiency. The application uses the photopic.txt file to make photopic diffraction efficiency calculations.

Note

User's need to install the MATLAB Runtime R2024a (24.1) version only. Any other version of MATLAB Runtime **will not** work with the DMD Diffraction Efficiency Calculator.

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3 Input Parameters

The user can change the input variables listed below according to the given application. Nominal values are populated in the GUI based on the given DMD chosen. Pixel Model input is a drop-down menu, while the other fields require the user to directly input a value.

3.1 Pixel Models (DMD Micromirror)

This input is a drop-down menu. The user can choose the pixel model to be analyzed from the drop-down list. The available DMD's are shown in Table 3-1.

Note

The application is not limited to the exact DMD configuration. Diamond and Manhattan configurations are allowed in the model even if no DMD currently supports that particular orientation. Please take careful considersation when choosing the appropriate orientation for your application.

3.2 Parameter Sweeps

The diffraction modeling application allows the user to sweep over the wavelength, illumination angle, tilt angle, illumination and projection $f/\#$ numbers. The application is initialized without the parameter sweep but can be turned on by selecting the Parameter Sweep button.

The user can input a start and stop value for the sweep along with a step size. For example, the wavelength can be swept over the visible spectrum in step sizes of 10nm as shown below:

Figure 3-1. Wavelegnth Parameter Sweep

Likewise, the other parameters can be swept. A start and stop angle are selected for the Illumination Angle and Tilt Angle parameters and a start and stop $f/\#$ is selected for the $f/\#$ (Illumination) and $f/\#$ (Projection) parameters.

Note

If the start and stop values for any parameter is the same, the model does not perform a sweep but runs the computation at that particular parameter only.

The step parameter is the scripts sampling rate. Step sizes can be any size. A smaller parameter step results in a finer, more accurate result but also takes longer to execute.

Another example is shown below for a tilt angle sweep. In this example the diffraction calculation calculates for 11º, 12º, and 13º mirror tilts.

Figure 3-2. Tilt Angle Paramater Sweep

3.3 Wavelength

The Wavelength inputs allows the user to enter the wavelength range over which the user can model. The unit of measurement is nanometers. Default values are 420nm to 700nm (visible spectrum). Sampling steps below 1nm can result in long execution times. A 2nm step is good as this provides accuracy and relatively fast computational speeds for a majority of applications.

3.4 Illumination Angle of Incidence

Typically, the illumination angle of incidence (AOI), defined as the central ray angle of the illumination light cone is twice that of the mirror tilt angle. However, the DMD is illuminated with a cone of light as shown in Figure 3-3. Standard illumination angles can be found in Table 3-1.

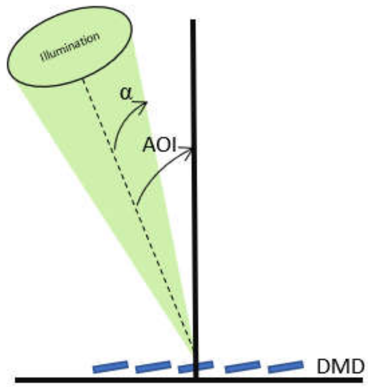

Figure 3-3. Illumination cone angle incident on a DMD

Note

α, the illumination half-cone angle, is equal to the DMD mirror tilt angle. The angle of incidence (AOI) is twice the mirror tilt angle and is defined from the normal to the DMD mirror array surface.

3.5 Tilt Angle

The Tilt Angle input follows the table below for a majority of applications. The user is given the flexibility to test the efficiency in the mirror on-state and the various maximum and minimum tilts. Table 3-1 shows typical DMD pixel models with the associated pixel pitch, tilt angles, and illumination angle.

Note

Please visit the specific DMD data sheet for more information regarding tilt angle min and max ranges.

Table 3-1. Pixel Geometries With Associated Tilt and Illumination Angles

Pixel Type	Pixel Pitch (μm)	Tilt Angle (Typ)	Illumination Angle
RDP	4.5	14.5°	29°
TRP	5.4	17°	34°
SST (at 12°)	5.4	12°	24°
SST (at 14.5°)	5.4	14.5°	29°
VSP Manhattan	7.56	12°	24°
VSP Diamond	7.637	12°	24°
HEP	9.0	14.5°	29°
SPD Manhattan	10.8	12°	24°
FTP Manhattan	13.68	12°	24°

3.6 *ƒ*/Number (Illumination and Projection)

Often the *ƒ*/# for illumination and projection are matched but having them as separate inputs allow the user flexibility for mismatched *ƒ*/# applications. The *ƒ*/# equation used in the model is shown below.

$$f\,\# = \frac{1}{2 * \sin(\theta)} \quad (1)$$

where θ is the Illumination and Projection cone half-angle. A table of typical *ƒ*/# and cone half-angles is shown in Table 3-2.

Table 3-2. Cone Half-Angles With Corresponding *ƒ*/#

Cone half-angle	*ƒ*/#
11	2.62
12	2.4
13	2.22
14	2.06
15	1.93
16	1.81
17	1.7

3.7 Enhance Slider

The diffraction image can have a very large dynamic range which is difficult to display in a single image. Thus, the displayed image visual enhancement (VE) or gain can be increased to better view the lower-intensity parts of the diffraction image. The Enhance slider bar can be changed from 1-10 allowing the diffraction pattern to have a multiplier of the selected slider value. The default enhancement is 1.

Figure 3-4 and Figure 3-5 are examples of modeled DMD diffraction pattern using various enhancement values. The enhancement is used to help understand the dynamic range of the diffraction pattern.

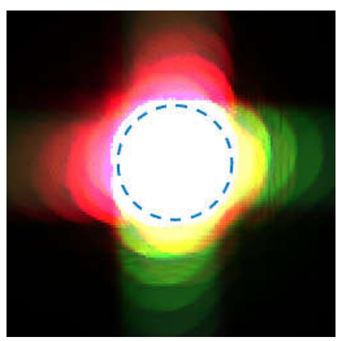

Figure 3-4. Enhancement multiplier value of 1

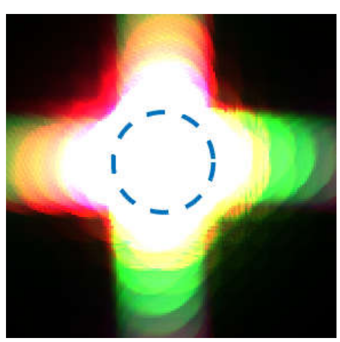

Figure 3-5. Enhancement multiplier value of 5

3.8 Diffraction Energy Plot

The diffraction energy plot is essentially the diffraction pattern but represented in 3D. Determining a particular order's magnitude in the 2D diffraction pattern can be difficult. The Diffraction Energy plot becomes useful when visualizing diffraction orders that do not heavily overlap and is most intuitive when a smaller wavelength range is applied. The plot is interactive and can give the user a more intuitive approach to the diffraction pattern simulation results. Figure 3-6 doesn't yield much information compared to the Diffraction Pattern plot, where as Figure 3-7 helps show the intensity variation between the orders which is more difficult to visualize in the Diffraction Pattern plot.

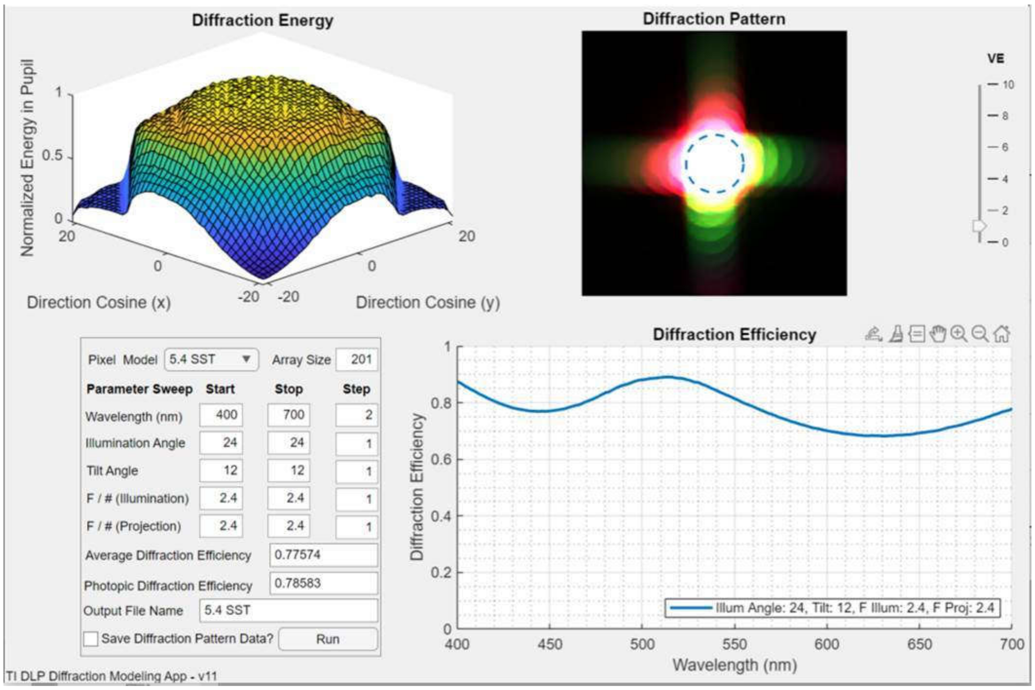

Figure 3-6. Overlapping Diffraction Orders With a Wide Wavelength Range

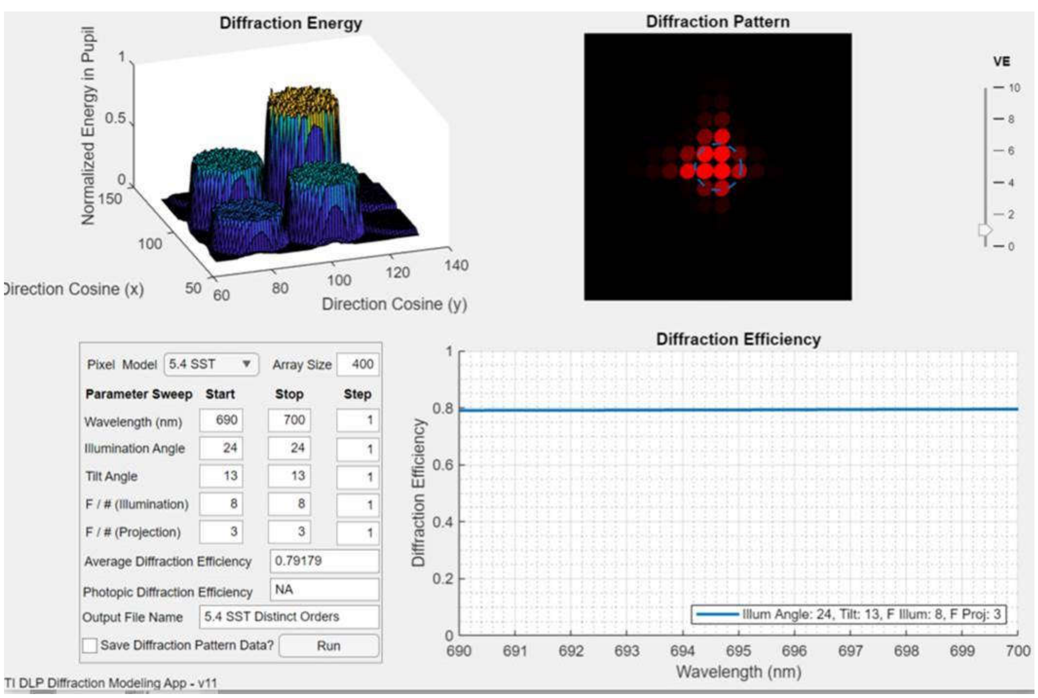

Figure 3-7. Non overlapping diffraction orders with a narrow wavelength range

3.9 Array Size

For applications with low ƒ/#s, the standard resolution for the solving array of 200 x 200 cells provides accurate models. However, moving to higher ƒ/# applications can require more resolution. From the table below, we can see that the accuracy improves as the resolution increases and tends to level out considerably with a 1600 x 1600 array size.

Table 3-3. Array Size Across Different f/#s With the Resulting Efficiency Values

Resolution Array Size	Diffraction Efficiency WL (400-700nm) @ ƒ/2.4	Diffraction Efficiency WL (400-700nm) @ ƒ/16	Diffraction Efficiency WL (400-700nm) @ ƒ/32
200 x 200	0.7755	0.2265	0.1049
400 x 400	0.7764	0.2121	0.0890
800 x 800	0.7768	0.2137	0.0914
1600 x 1600	0.7767	0.2155	0.0928
3200 x 3200	0.7769	0.2150	0.0923
6400 x 6400	0.7768	0.2150	0.0932

As array size increases the accuracy and variation improve. Larger array sizes can cause substantially longer modeling times with the tradeoff of higher accuracy simulations. Tests can be run to verify that the accuracy is good for the given application. The resolution array size can be changed by inputting the desired value into the Array Size input field.

3.10 Output File Name

An excel document with a summary of the diffraction efficiency results is generated in the same folder as the TI DLP Diffraction Modeling application. This field allows the user to name the output Excel file name. This file can be used for additional plots and analysis.

If the user chooses to check the “Save Diffraction Pattern Data?” box, an additional excel document is stored with the “Output File Name” + “Diffraction_Pattern”. This data corresponds to the energy distribution of the diffraction pattern. This data is the raw data used to generate the diffraction pattern and diffraction energy plots.

3.11 Average Diffraction Efficiency and Photopic Diffraction Efficiency

These fields are not user inputs. The output gives the calculated average diffraction efficiency and average photopic diffraction efficiency. The average diffraction efficiency is calculated by taking an average of the diffraction efficiency values across the specified wavelength spectrum. The photopic diffraction efficiency is taken by multiplying the diffraction efficiency with the normalized photopic response at the corresponding wavelengths. This is done as a summation taken across the entire wavelength spectrum. The result is then divided by the summation of the photopic response values across the wavelength spectrum.

$$Photopic\ Efficiency = \frac{\sum_{\lambda_i} S(\lambda_i)\ Phot(\lambda_i)\ Diffraction\ Efficiency(\lambda_i)}{\sum_{\lambda_i} S(\lambda_i)\ Phot(\lambda_i)} \tag{2}$$

S (λ_i) is the source spectrum and Phot (λ_i) is the photopic curve. The average is then taken across the spectrum to show the value displayed in the application.

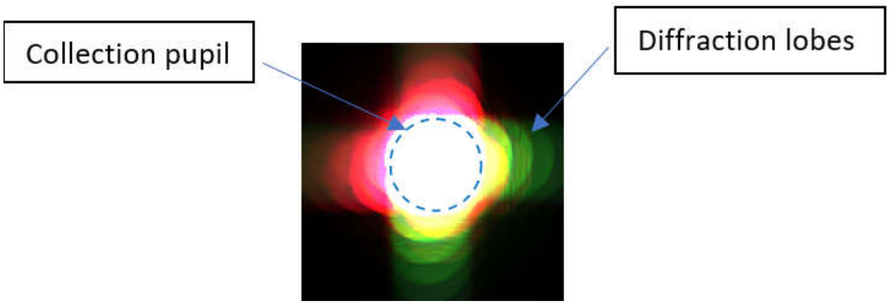

Figure 3-8. Diffraction pattern. Light inside the dotted blue line is collected by the projection optics. Light outside the dotted blue line is lost in diffraction lobes. Diffraction efficiency is light collected divided by total light.

3.12 Apodization

Upon opening the application, the Pupil drop down menu is set to Uniform. This indicates that the rays in the pupil are going to have uniform weights. This can be adjusted by changing the Pupil drop down menu to Gaussian. This initializes a weighted gaussian pupil distribution across the ray profile. The Gaussian Value can be adjusted according to a given system apodization. The Apodization Profile plot indicates the chosen profile used in every simulation. The plot shows a ray uniformity Pupil Cross Section for the given profile chosen in the simulation. The black lines on either side of the profile indicates the pupil or f/# boundaries chosen. The apodization functionality is determined by the following equation:

$$Apodization = \exp\left(-\ gaussian_{val}\left(\frac{radius}{cone_{angle}}\right)^2\right) \tag{3}$$

where $gaussian_{val}$ is the value inserted by the user. This value dictates the steepness of the gaussian profile. Higher values are going to result in steeper gaussian profiles. Radius is f/# radius being applied. The $cone_{angle}$ is f/# cone angle in direction cosine space. Please see Example 5.5 below for more details on how to use Apodization in the GUI.

3.13 Run Simulation

Once all of the values are entered, click the Run button to begin the simulation. The processing time can take up to a few minutes to execute depending on the parameters selected.

The resulting plots include the diffraction pattern in the far-field, the diffraction energy, which is a 3D interactive plot of the diffraction pattern, and the diffraction efficiency curve by wavelength. The average diffraction efficiency boxes populate and excel files are created with the diffraction efficiency by wavelength values and the diffraction energy distribution if the user selects the “Save Diffraction Pattern Data?” check-box.

4 Coordinate System

The diffraction model is based on a spherical coordinate system as shown in Figure 4-1. The tilt and illumination angles are defined by theta (θ) and phi (Φ) angles in the coordinate system.

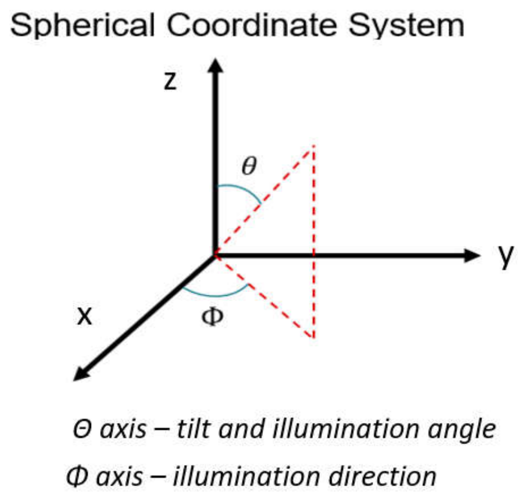

Figure 4-1. Spherical Coordinate System Defined by Theta and Phi Angles for a Given Mirror Array Plane

An example of a torsional design is presented in Figure 4-2 and a cantilever design in Figure 4-6. On and off state diffraction patterns are shown with their given theta and phi angles. The illumination direction, pupil diagram, and on and off rays are represented to help clarify the conditions that will be used when modeling diffraction. **TRP pixel is the only cantilver pixel design; all other pixel models utilize a torsional design.**

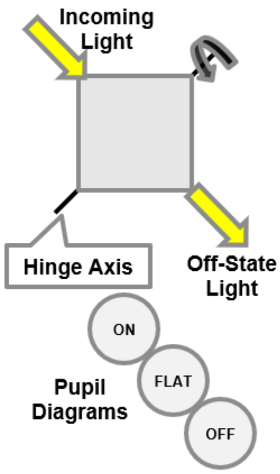

Figure 4-2. Torsional 12º Mirror Tilt Design With Corner Illumination with the pupil diagram showing On, Flat, and Off states of the mirror

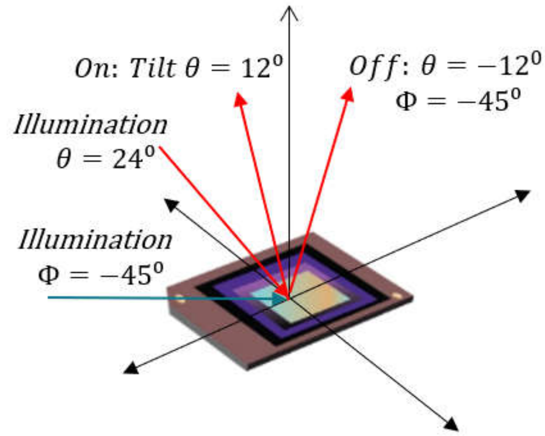

Figure 4-3. On and Off State Illumination and Tilt Angles with their Associated Rays on a DMD

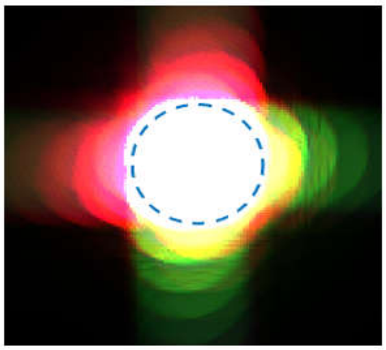

Figure 4-4. Mirror On State Diffraction Pattern Model with Mirror (θ = 12º, Φ = -45º), Illumination (θ = 24º, Φ = -45º)

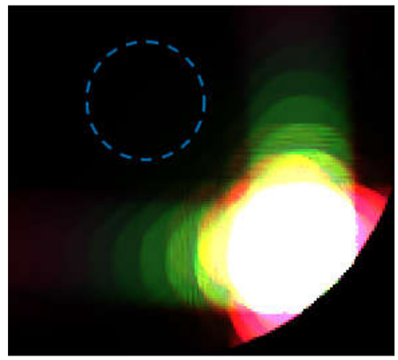

Figure 4-5. Mirror Off State Diffraction Pattern Model with Mirror (θ = -12º, Φ = -45º), Illumination (θ = 24º, Φ = -45º)

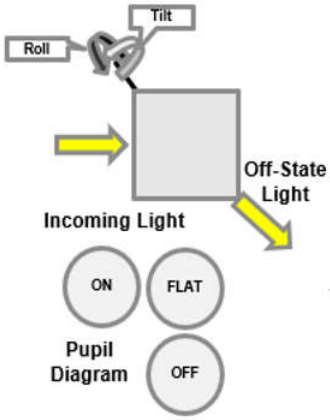

Figure 4-6. Cantilever 17º Mirror Tilt Design With Side Illumination with the pupil diagram showing On, Flat, and Off states of the mirror

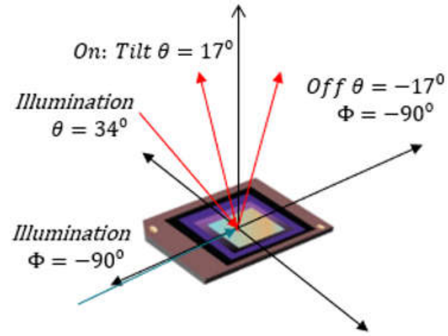

Figure 4-7. On and Off State Illumination and Tilt Angles with their Associated Rays on a DMD

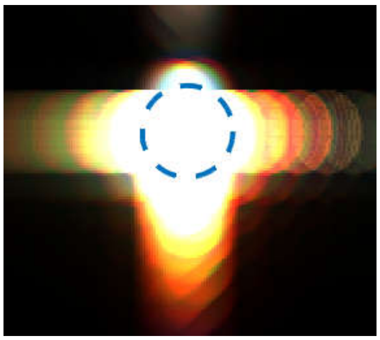

Figure 4-8. Mirror on State Diffraction Pattern Model with Mirror (θ = 17º, Φ = 90º), Illumination (θ = 34º, Φ = 90º).

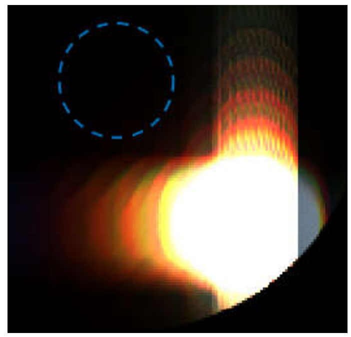

Figure 4-9. Mirror Off State Diffraction Pattern Model with Mirror (θ = -17º, Φ = -90º), Illumination (θ = 34º, Φ = 90º)

5 Examples

This section is going to provide specific examples of the TI DLP Diffraction Modeling application functionality. Each example displays the diffraction pattern (left) and the diffraction efficiency curve (right) with the input parameters (bottom). The results closely follow the interface that the user interacts with and can offer intuition for the applications capabilities.

Note

The colored dotted circle on the diffraction pattern represents the projection pupil.

High F/Number Illumination demonstrates diffraction modeling using illumination and projection ƒ/#'s that are relatively large compared to traditional DMD ƒ/#. Figure 5-1, Figure 5-2, and Figure 5-3 illustrate the tilt angle variation range from 11º to 13º and how the tilt angle effects the diffraction efficiency for high ƒ/#. Figure 5-4 is going to demonstrates how to sweep parameters and overlay diffraction efficiency curves with varying device parameters.

5.1 High F/Number Illumination

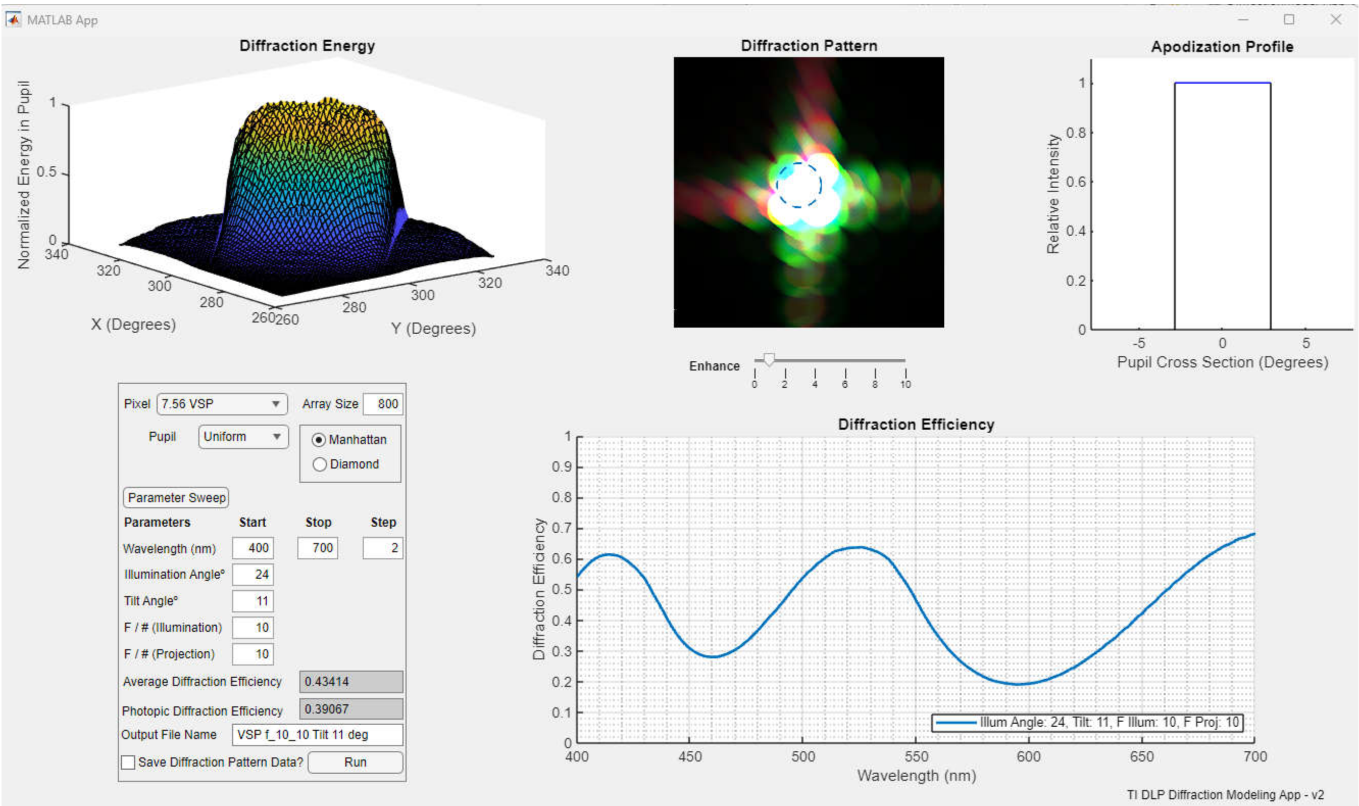

Figure 5-1. Illumination and Projection ƒ/# are Set to 10 With an 11º Tilt Angle

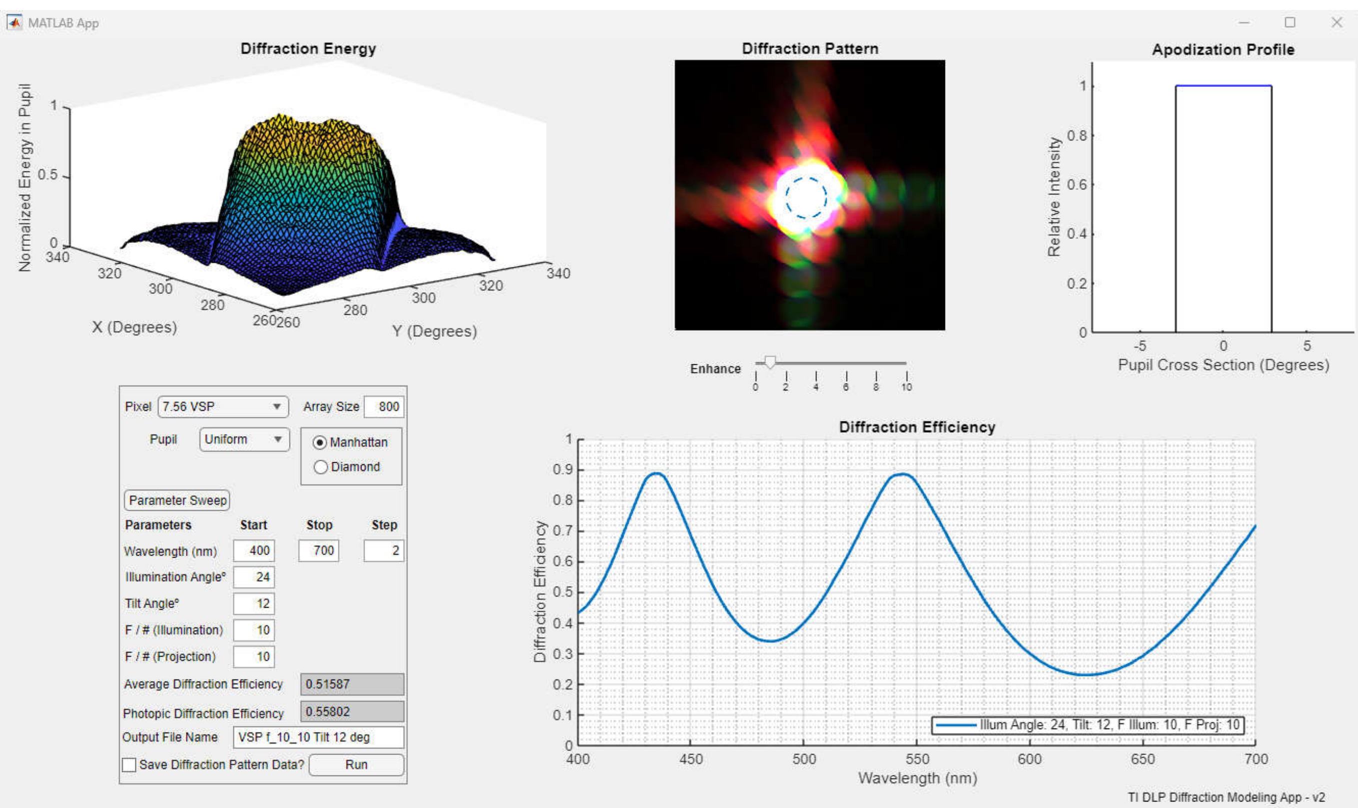

Figure 5-2. Illumination and Projection ƒ/# are Set to 10 With a 12º Tilt Angle

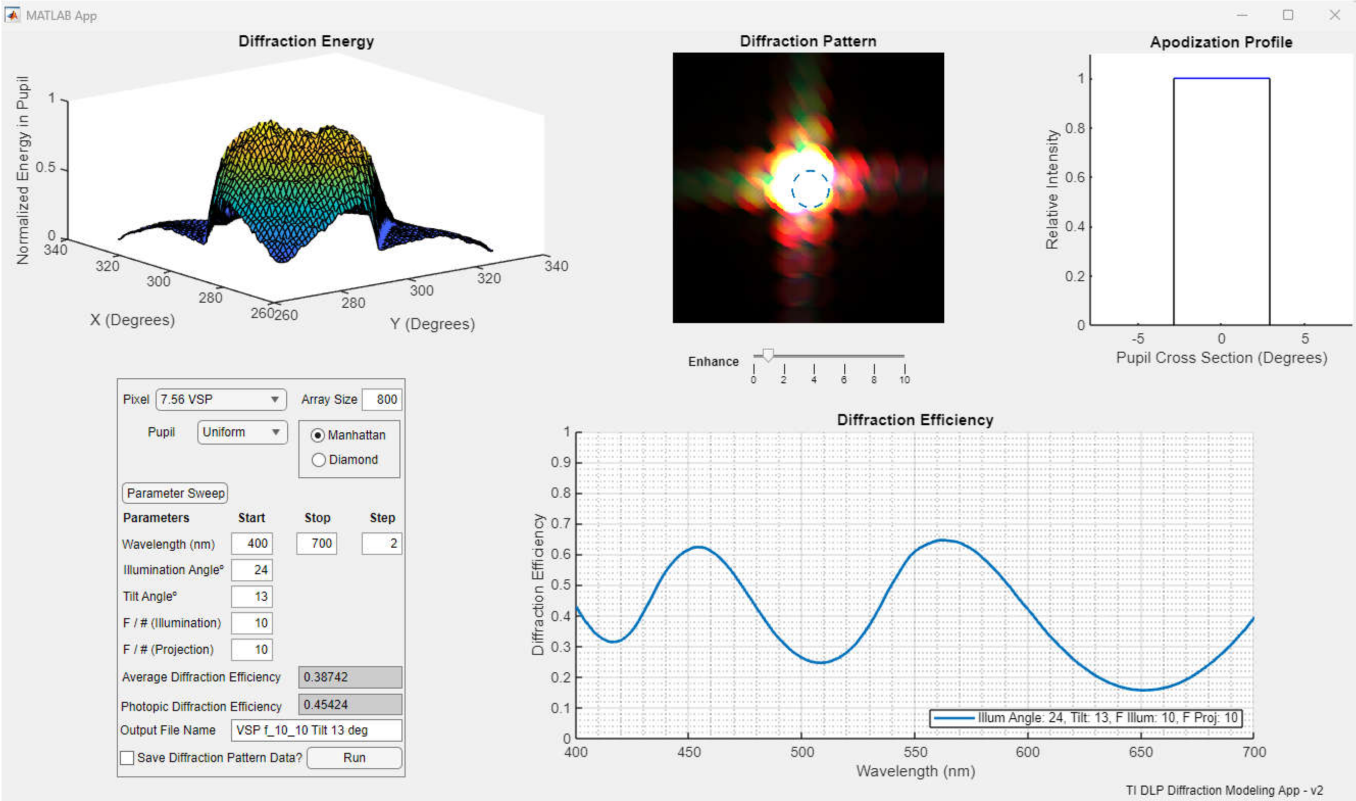

Figure 5-3. Illumination and Projection ƒ/# are Set to 10 With a 13º Tilt Angle

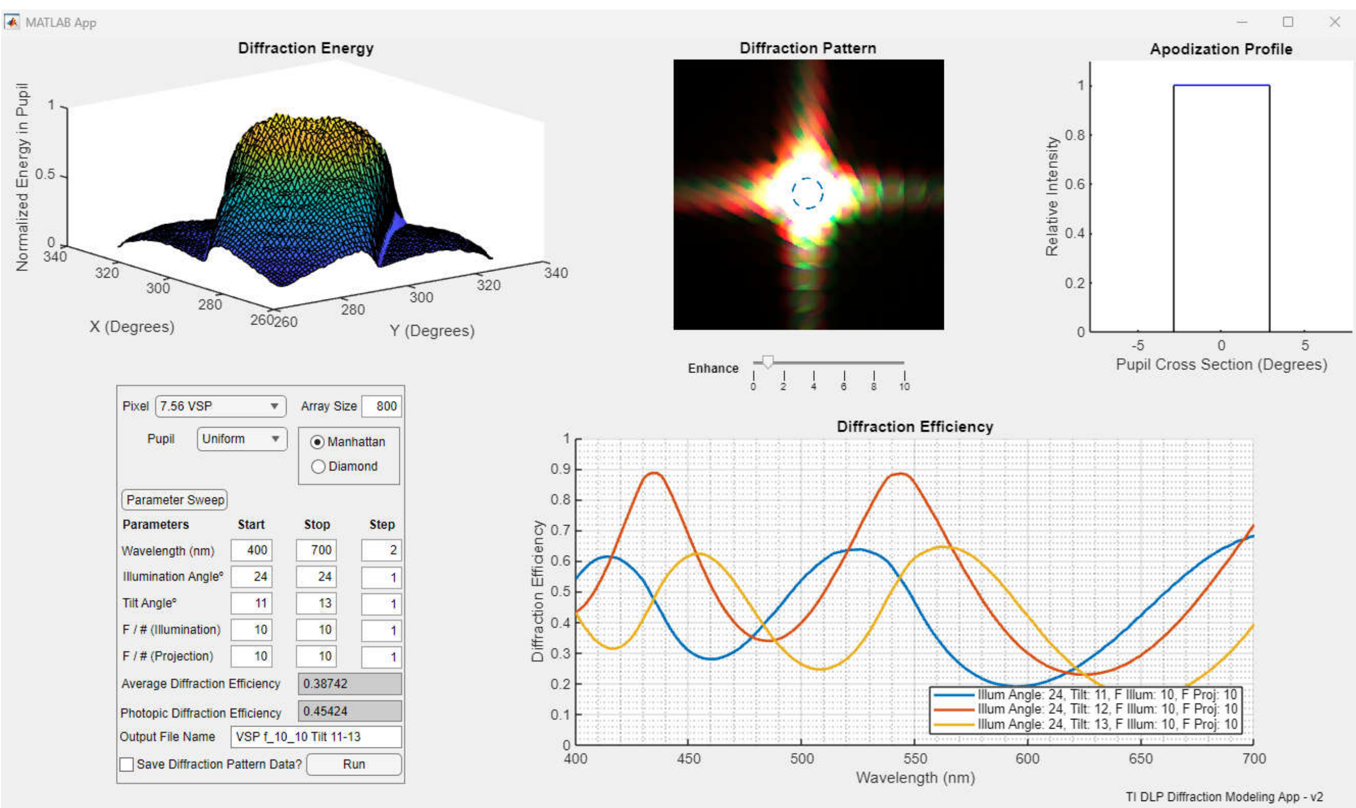

Figure 5-4. Illumination and Projection ƒ/# are Set to 10 With a Tilt Angle Sweep Between 11-13º

5.2 Mismatched Illumination and Projection F/Number

Mismatched Illumination and Projection F/Number demonstates the uses of mismatched ƒ/#'s. Figure 5-5 uses a matched illumination ƒ/# of 2.4 with a projection ƒ/# of 2.4 and Figure 5-6 uses mismatched ƒ/#'s so that the illumination is f/3 and the projection is f/2.4. The resultant diffraction efficiency is increased as the larger projection aperture is able to collect more light.

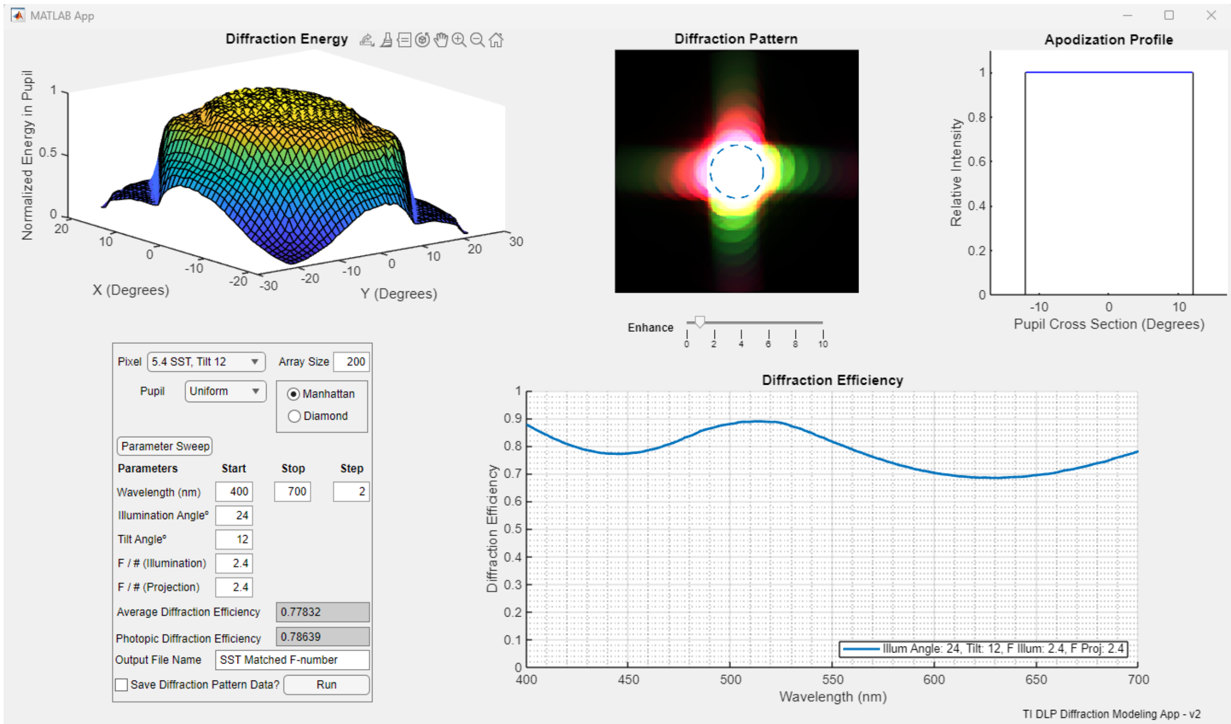

Figure 5-5. Matched Illumination and Projection ƒ/# of 2.4

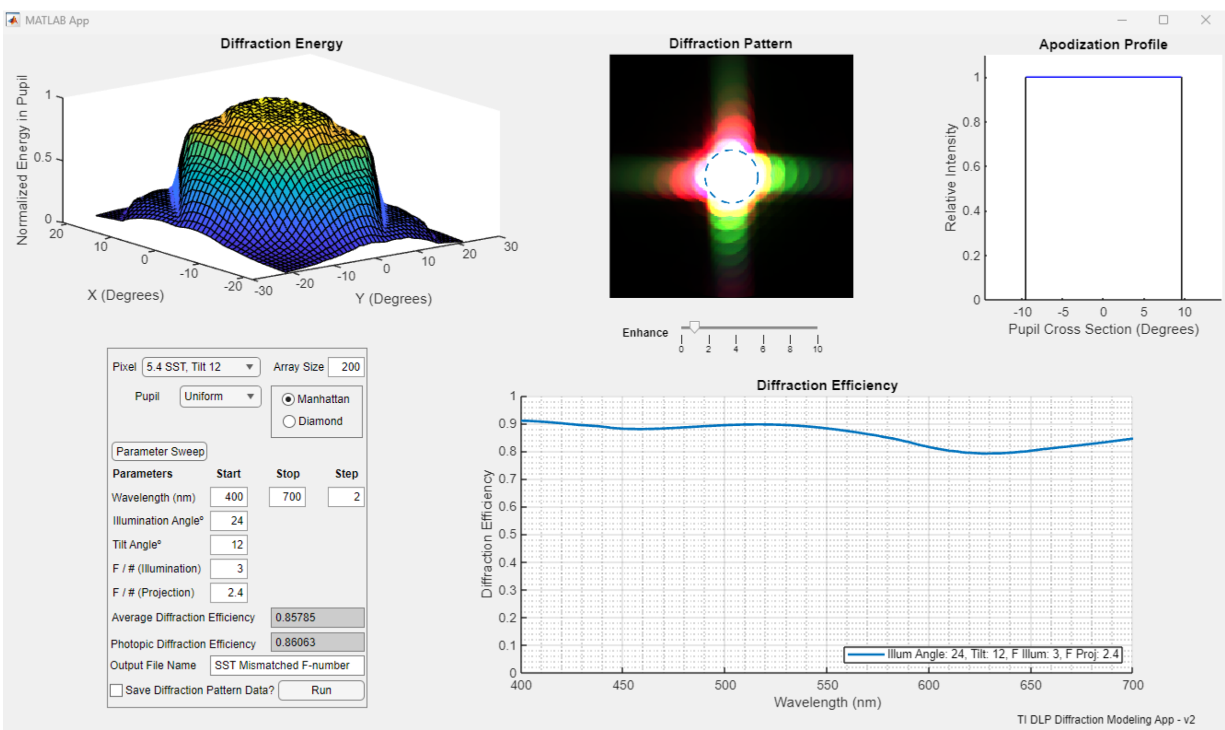

Figure 5-6. Mismatched Illumination of 3 and Projection ƒ/# of 2.4

5.3 Cantilever Versus Torsional With Same Pixel Pitch

Cantilever Versus Torsional With Same Pixel Pitch compares a 5.4 mirror pitch TRP cantilever design to a 5.4 mirror pitch SST torsional design. Even though the pixel pitch is identical, the diffraction efficiencies are different due to the inherent optical differences between the cantilever and torsional tilt mechanisms and the difference in pitch when illuminated from the side versus the corner of the mirror. The 5.4 SST illumination is from the mirror corner making the pitch $\sqrt{2}*5.4$ vs. the 5.4 TRP illumination which is from the mirror edge, making the pitch 5.4.

Figure 5-7 and Figure 5-8 use matched F/numbers at 2.4 to directly compare the TRP and SST pixels.

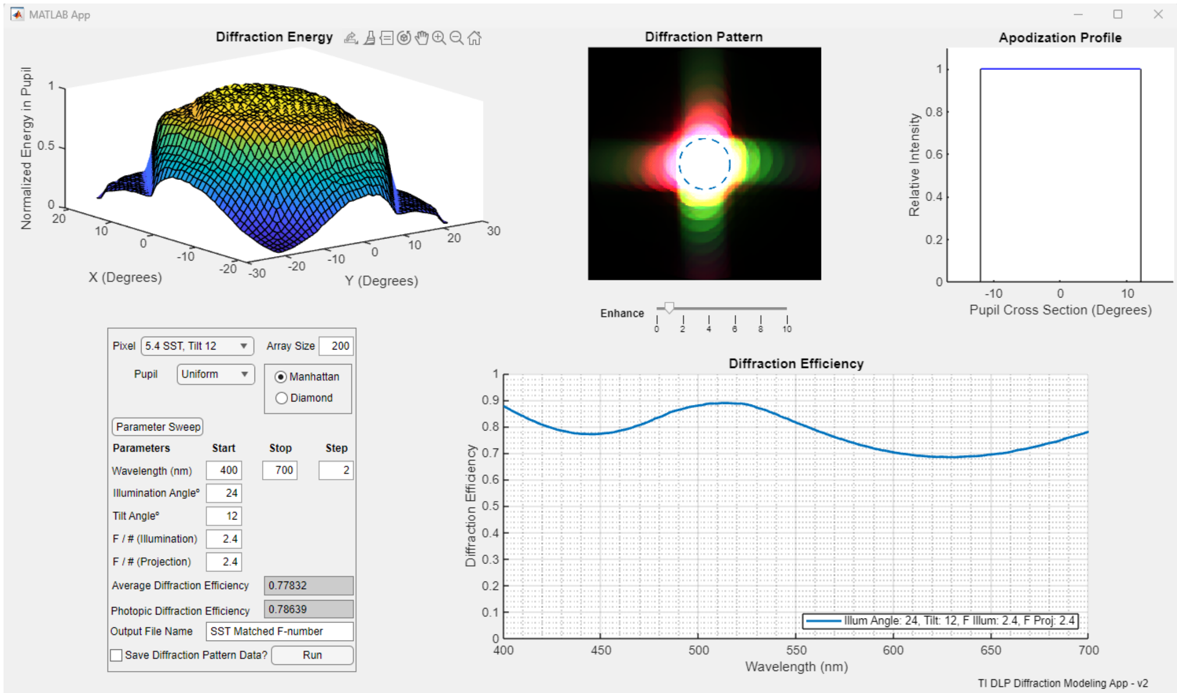

Figure 5-7. SST Torsional Design With a 5.4 Pitch Pixel

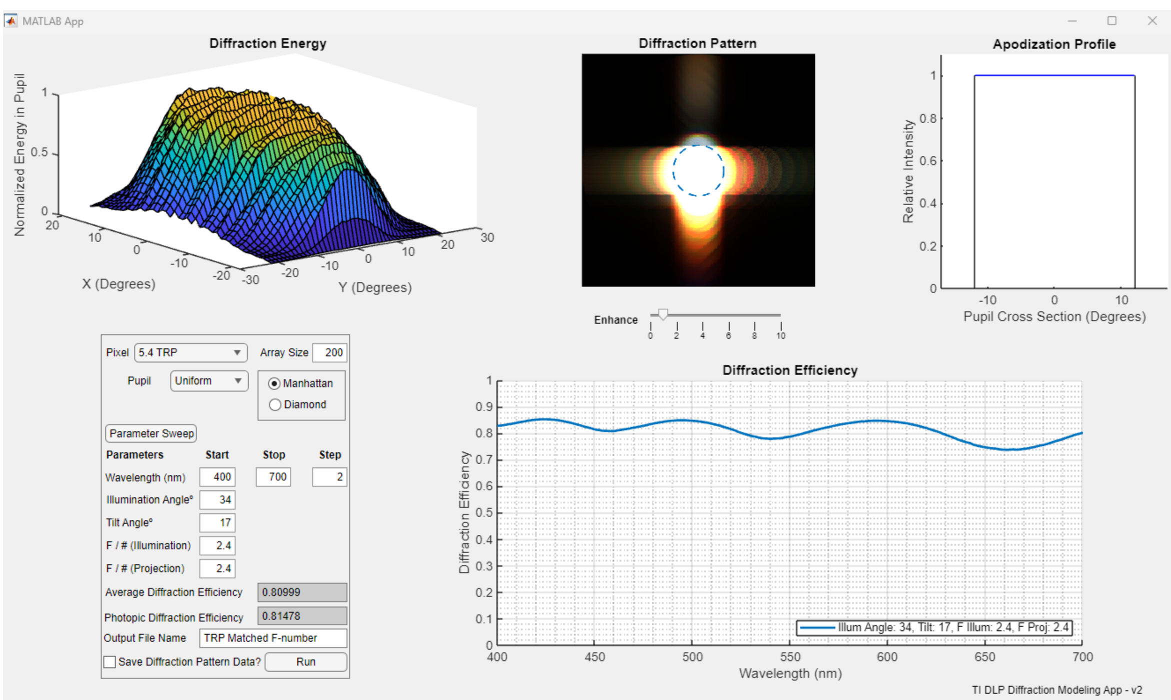

Figure 5-8. TRP Cantilever Design With a 5.4 Pitch Pixel

5.4 Side Diamond Diffraction Pattern

Figure 5-9 demonstrates a side diamond diffraction pattern using a 4.5 RDP pixel

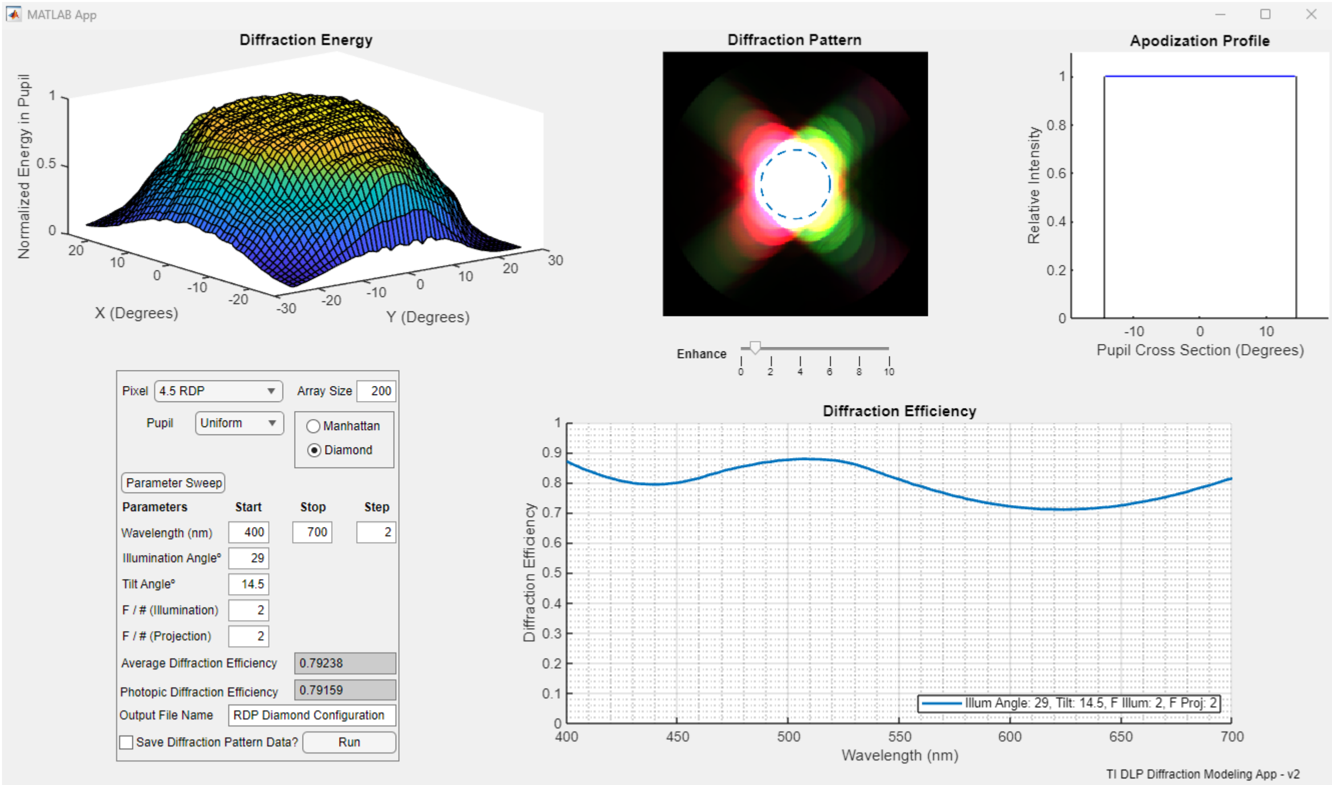

Figure 5-9. 4.5 um pitch pixel. Side Diamond configuration enabled to more accurately model diffraction pattern. Side lobes for an X pattern instead of a cross

5.5 Apodization

Figure 5-10 demonstrates how to use the Pupil Apodization. Select “Gaussian” from the Pupil drop down menu. Input “Gaussian Factor”. In this case, 1 is the input for the Gaussian Factor. The Apodization Profile plot is updated to show the Relative Intensity across the Pupil Cross Section

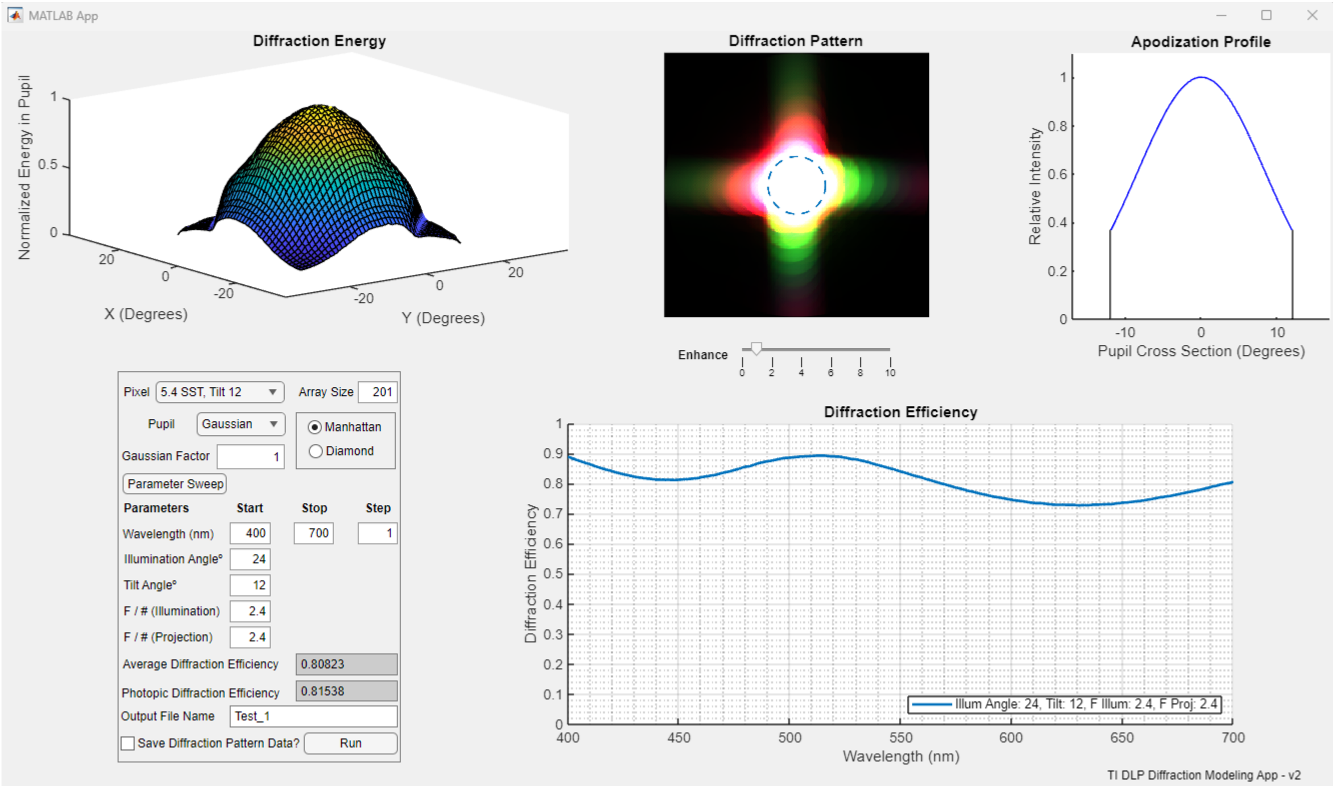

Figure 5-10. Pupil apodization using a gaussian factor. Higher gaussian factors result in steeper apodization profiles

Trademarks

All trademarks are the property of their respective owners.

6 References

1. J. E. Harvey, *Linear Systems Formulation of Non-Paraxial Scalar Diffraction Theory*, publication.
2. Texas Instruments, *DMD Optical Efficiency for Visible Wavelengths*, application note.
3. Texas Instruments, *Using Lasers with DLP DMD technology*, application note.

7 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (May 2024) to Revision A (September 2025) **Page**

- The required MATLAB Runtime version for GUI has been updated in Installation and setup............................2
- Added a note regarding Diamond and Manhattan modeling configurations in Section 3.1...............................3
- Added information regarding Parameter Sweep button in Section 3.2..3
- Updated Table 3-1 which now includes the RDP pixel..4
- Updated title to Enhance Slider in Section 3.7 5
- Added Figure 3-8 to illustrate collection pupil vs. diffraction lobes from a diffraction pattern...........................8
- Added new section regarding Apodization; Section 3.12 8
- Updated figures in Section 5.1 to account for Apodization..11
- Updated figures in Section 5.2 to account for Apodization..14
- Updated figures in Section 5.3 to account for Apodization..15
- Added new example regarding side diamond diffraction patterns; Section 5.4 16
- Added new example regarding Apodization; Section 5.5 17

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