Modeling Diffractive Effects due to Micro-lens Arrays on Liquid Crystal Panels in Projectors

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ABSTRACT

The components in optical projectors are becoming increasingly smaller due to the need for increased output resolution and the desire for small form-factor devices. One such component is Liquid Crystal (LC) panels, that utilize periodic micro-lens arrays which become more sensitive to diffractive effects as the period becomes near/sub wavelength. This paper explores the diffraction effects within these systems through numerical modeling. Traditionally Ray tracing techniques have been used for analyzing projection systems and has led to significant improvements in illumination uniformity and efficiency. However, increasingly complex projector designs that incorporate smaller geometric features like micro/nano lens arrays, including coherent diffraction and interference effects arising from such structures, cannot be handled by ray-tracing approaches alone. Rigorous electromagnetic (EM) wave optics based techniques, such as finite-difference time-domain (FDTD) and rigorous coupled wave analysis (RCWA) which solve Maxwell's equations must be used. These rigorous EM techniques, however, have difficulty in analyzing the larger projector structures due to computational resource limitations. We use a mixed-level optical simulation methodology which unifies the use of rigorous EM wave-level and ray-level tools for analyzing projector performance. This approach uses rigorous EM wave based tools to characterize the LC panel through a Bidirectional Scattering Distribution function (BSDF) file. These characteristics are then incorporated into the ray-tracing simulator for the illumination and imaging system design and to obtain the overall performance. Such a mixed-level approach allows for comprehensive modeling of the optical characteristic of projectors, including coherent effects, and can potentially lead to more accurate performance than that from individual modeling tools alone.

Keywords: Optical Projectors, optical simulation, micro-lens arrays, finite-difference time-domain (FDTD), ray-optics modeling, rigorous coupled wave analysis (RCWA), photonic simulation, mixed-level simulation

1. INTRODUCTION

The components in optical projectors are becoming increasing smaller due to the need for increased output resolution and desire for small form-factor devices [1]. Digital projectors have three main parts: an illumination system, an imager (LC panel, LCOS, or DMD) and an imaging (lens) system. This paper explores the diffraction effects within projectors that utilize micro-structured LC panels as the imager, through the use a mixed-level optical simulation methodology. This unified approach incorporates rigorous EM wave-level with ray-level tools for analyzing projector performance. This allows for comprehensive modeling of the optical characteristic of projectors, which can potentially lead to more accurate performance than using individual modeling tools alone.

The design of optical projectors relies heavily on computational simulation to provide understanding of the underlying physics, providing design insights, and increasing performance. Projectors are composed of components with a wide range of length and geometric scales that cannot be accurately and efficiently simulated through a single numerical technique. Ray-optics based methods such as Monte Carlo ray-tracing (RT) are commonly used to analyze the illumination system and the imaging (lens) system designs. However, ray-tracing techniques are based on the geometric optics approximation and fail to address the diffractive nature of micro-scale and/or sub-wavelength geometric features associated with the LC panel itself. On the other hand, rigorous electromagnetic (EM) wave-optics based techniques such as rigorous coupled wave analysis (RCWA) and finite-difference time-

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domain (FDTD) can be used to model the micro-scale and/or sub-wavelength nature of a LC panel, but cannot be used to analyze larger bulk optic components due to computational limitations. It becomes clear that a mixed-level simulation approach is required to circumvent the limitations of the individual numerical techniques.

This paper presents the use of a mixed-level simulation approach which unifies the use of EM wave-level and ray-level tools to model a projector system. This approach uses rigorous EM wave based tools to characterize the micro-scale LC panel structure including micro-lens arrays. The output of these simulations is used to generate polarimetric Bidirectional Scattering Distribution Function (BSDF) files which are then applied as surface properties in the ray-tracing simulation. This surface property defines how an incident ray's energy and direction are modified at material interface surface. The illumination and imaging system can be designed through RT alone and are not discussed in detail. Mixed-level simulation combining EM and ray-tracing are used to analyze the overall performance of the projector. In section 2, we provide a brief description of the simulation techniques used. Section 3 covers the design of the LC panel using an RCWA-based EM simulator and section 4 uses the EM simulation results in the context of the RT simulator to perform the overall analysis of the projector system.

2. SIMULATION TECHNIQUES

The following section reviews the individual numerical techniques used in this paper as well as presenting a combined methodology for a multi-level approach.

The LC panel is simulated using the rigorous coupled wave analysis (RCWA) algorithm which is widely used to simulate the diffraction from periodic structures [2,3]. The RCWA algorithm typically requires less memory and is faster than FDTD, but can only be used for periodic structures. DiffractMOD® [4], a commercially available software tool, was used for the RCWA simulations. The illumination and imaging systems are simulated using Monte Carlo Ray-Tracing (RT) which models the system as a collection or rays with position, angle, and magnitude [5]. LightTools® [6], a commercially available software tool, was used for the RT simulations presented in this paper. CODEV [7] was used for the lens system design of the Imaging System. A Bidirectional Scattering Distribution Function (BSDF) was used to characterize the scattering properties from the surface of an arbitrary structure [8]. Traditional BSDF's are scalar and do not account for polarization. However, a more general form of the BSDF is the polarimetric BSDF which, in addition to the radiance, also characterizes the polarization of the scattering. These characteristics are essential to include especially when modeling polarization sensitive structures. A DiffractMOD® based BSDF Utility [9] was used to generate the required BSDF's that can then be traced in LightTools® [6]. Our mixed-level simulation approach is summarized as follows. We first use a rigorous EM wave-based tool [4] to characterize the LCD panel. The complete scattering information calculated by this is saved as a polarimetric BSDF. We then apply the calculated BSDF as a surface property within the ray-based tool. Finally, we trace rays to model the overall performance of the system. Further details of these methods, including the mixed-level method can be found in our previous work [10-12].

This paper will primarily focus on designing the LC panel to study projector efficiency, and will then briefly show the results from mixed-level simulations of the projector system. A detailed illumination system design and the imaging system design can be performed using RT alone and is not highlighted in this work.

3. LC PANEL DESIGN

The illumination and the imaging aspects of a projector are 'large' optical problems that are accurately simulated via ray-tracing. LC panels are 'small' optical problems that are accurately simulated through wave-level simulation. Here 'large' and 'small' are defined based on the structure size compared to the wavelength of light. Periodic micro-lens arrays within the LC panel transmit power in high diffraction orders and potentially causing image distortion. Diffractive effects become more important as pixels get smaller to support higher resolutions (e.g. 4k).

3.1 LC Panel Structure

The LC structure studied is shown in Figure 1.

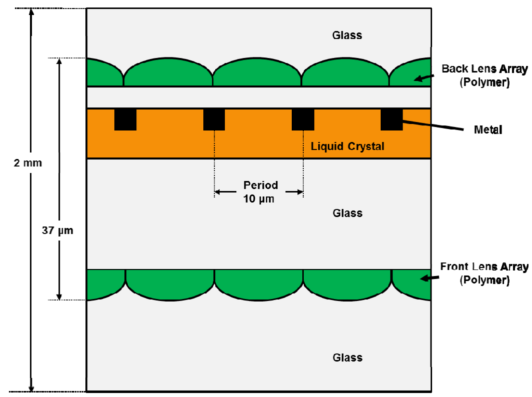

Figure 1. LC panel structure

The LC panel studied consists of a glass substrate, polymer-based micro-lens arrays on the front and back sides, and a liquid crystal layer with metallic pathways. The dimensions are shown in Figure 1; the refractive indices at λ = 550nm are n=1.46 for glass, (n=2.898, k= 4.32) for metal, n = 1.75 for the lenses, and (n_o= 1.75, n_e = 1.53) for the anisotropic liquid crystal. The micro-lenses used are spherical and symmetric, and have a radius of 7 µm.

3.2 Simulation Parameter Convergence Study

It is important to ensure that the results are converged with respect to the simulation settings. The two main simulation settings in the RCWA algorithm are the number of harmonics and the thickness of layers used to discretize the micro-lens arrays along the primary propagation direction.

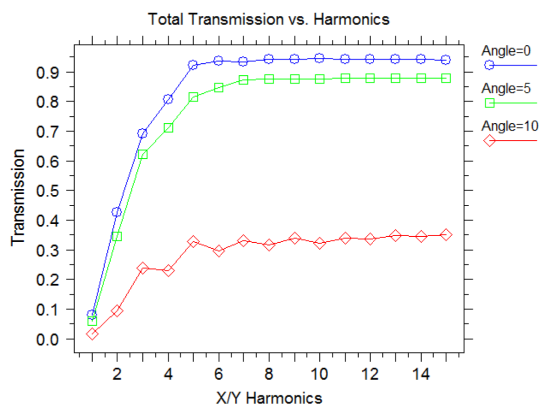

Figure 2. Convergence of RCWA simulations with number of Harmonics.

The convergence plot in Figure 2 show that the simulation results converged at 8 harmonics in both transverse directions. We also found that a layer thickness of Δz = 0.125 µm in the lenses was required to obtain converged results. At these settings, each RCWA simulation used around 1.5 GB of RAM and took ~1.5 minutes on a typical multi-core desktop.

3.3 RCWA Results for LC Panel

Figure 3 shows converged simulation results from a representative RCWA simulation. The micro-lens arrays are seen to focus the light through the structure to avoid reflection and/or absorption losses from the metal in Figure 3(a). Figures 3(b) and (c) show the transmitted and reflected near fields at the simulation domain interfaces. Figures

3(d) and (e) show the transmitted and reflected diffraction efficiencies as a function of diffraction order. The angular spacing of the diffraction orders at this period of 10 µm is ~3.2°.

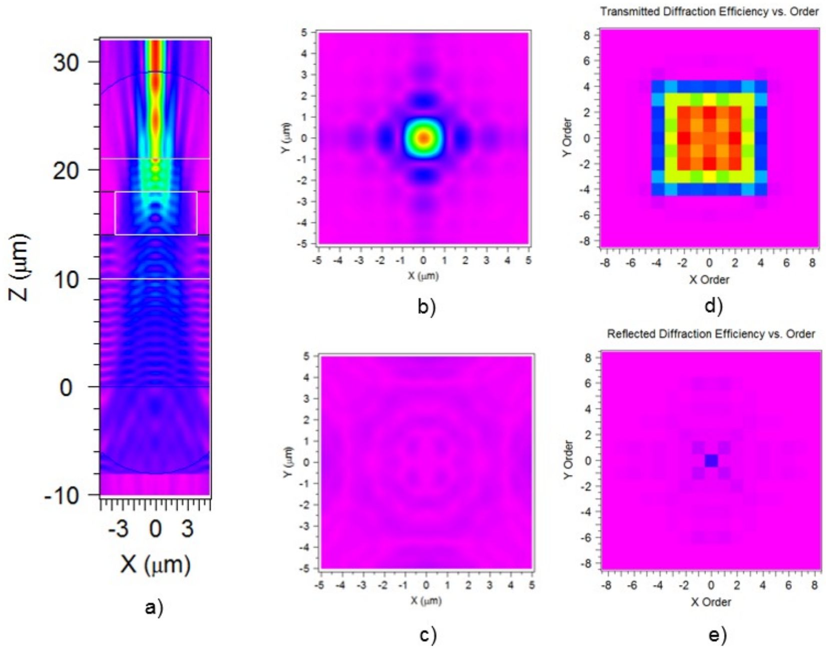

Figure 3. RCWA simulation results for normal incidence: a) field profile (Ex) within the LC panel, b) transmitted near field, c) reflected near field, d) transmitted diffraction efficiency, and e) reflected diffraction efficiencies.

The results in Figure 3 were at normal incidence and could change substantially at different input angles. The range of input angles and the power distribution of light incident on the LC panel is controlled by the illumination system. The optimal range of input angles can be estimated by scanning over the input angle. Figure 4 shows how the transmitted and reflected power changes as a function of the input angle of the incident beam. This LC panel functions efficiently when used with an illumination system that has an angular range of up to ~5° off normal.

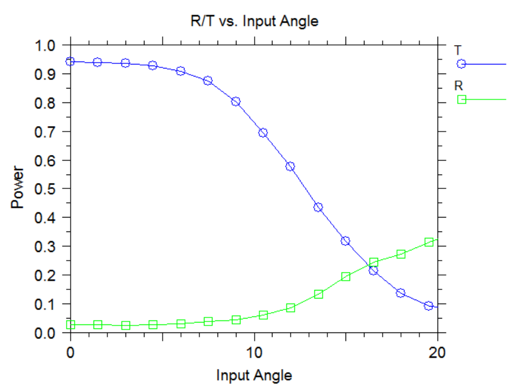

Figure 4. Calculated transmission (T) and reflection (R) as a function of incident angles.

3.4 Estimation of Projector Efficiency

The projector efficiency can be accurately modeled using the mixed-level technique that combines EM and RT. However, in this section, we will use a simplified approach: the light incident on the LC panel will be at discrete input angles, the imaging system will be treated as an ideal system with a certain angular acceptance cone. This assumption allows us to estimate the projector efficiency directly from the transmitted orders and angles obtained with RCWA.

The estimated efficiency metric for a 10 μm period LC panel are shown in Figure 5. Figure 5(a) shows the transmitted diffraction efficiency for each order. The sum of the power in all these orders represents the total transmission, but the imaging system will not capture all these orders. Only orders that are within the angular acceptance cone will be captured. The two circles illustrate two possible angular acceptance cones of 12° and 26°.

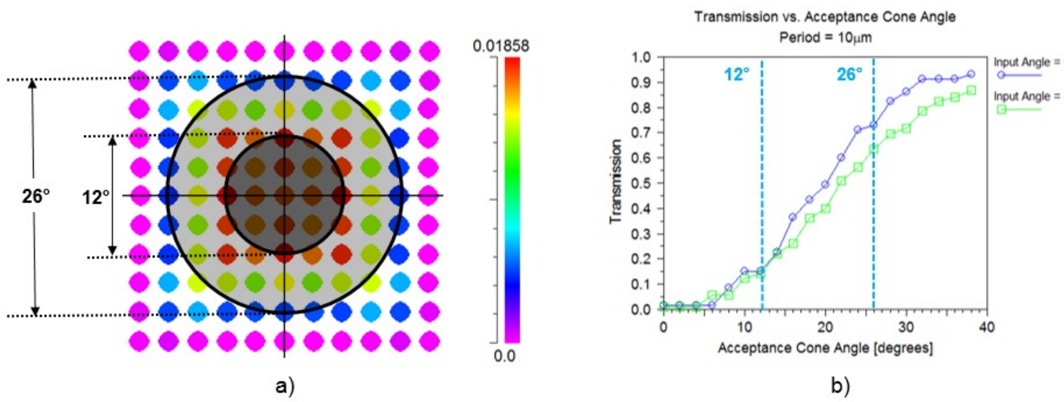

Figure 5. a) Illustration of transmitted diffraction orders and representative acceptance cones, and b) estimated efficiency as a function of the acceptance cone angle of the ideal lens system.

Figure 5(b) shows the estimated transmission efficiency, subsequently called efficiency, as a function of acceptance cone angle for two input angles. Here the input angle refers to the angle of the light incident on the LC panel from the illumination system. The actual projector illumination system will produce a spread of angles, however here we model collimated light at discrete input angles. At an input angle of 0°, we calculate 94% efficiency for a imaging system with a >40° acceptance cone, 73% for a 26° cone, and 15% for a 12° cone. At an input angle of 5°, we calculate 86% efficiency for a imaging system with a >40° acceptance cone, 63% for a 26° cone, and 14% for a 12° cone.

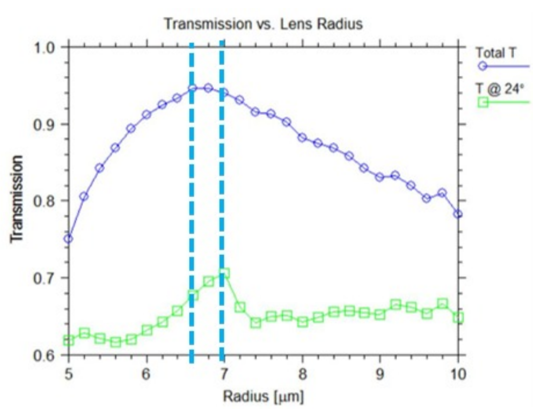

Figure 6. Estimated efficiency with (green, assuming a 24° acceptance cone) and without (blue) a projector imaging system. Note that the optimal radius is different for each case.

The efficiency metric used should represent the performance of the entire system and not just the LC panel. To illustrate this, we performed a parameter scan over the micro-lens radius while measuring the total transmission through a standalone LC panel as well as the estimated efficiency calculated through the LC panel, followed by an ideal lens system with an acceptance cone of 24°. The results, in Figure 6, show that the optimal radius differs based on the metric chosen. The metric based on total transmission predicts an optimal radius of 6.6 µm whereas the metric that includes the acceptance cone predicts an optimal radius of 7.0 µm. These results are for top/bottom symmetric micro-lenses, other micro-lens shapes may further improve efficiency including non-symmetric lenses, conic lenses and novel shapes.

3.5 Effect of Pixel size on Efficiency

The miniaturization of optical projectors in recent years requires smaller pixels in order to maintain a display resolution or achieve higher resolution. Diffraction effects become more important as pixel size decreases, and must be included in the design and simulation process. Ray-tracing alone cannot directly include such effects, a mixed-level approach is required. Figure 6 shows the simulated results at pixel sizes of 5, 10, and 15 µm. Figures 7(a), (c) and (e) show the transmitted diffraction orders for various periods at an input angle of 0°, where ‘input angle’ refers to the angle of the light incident on the LC panel from the illumination system. The angular spread of the transmitted orders gets smaller as the pixel size decreases.

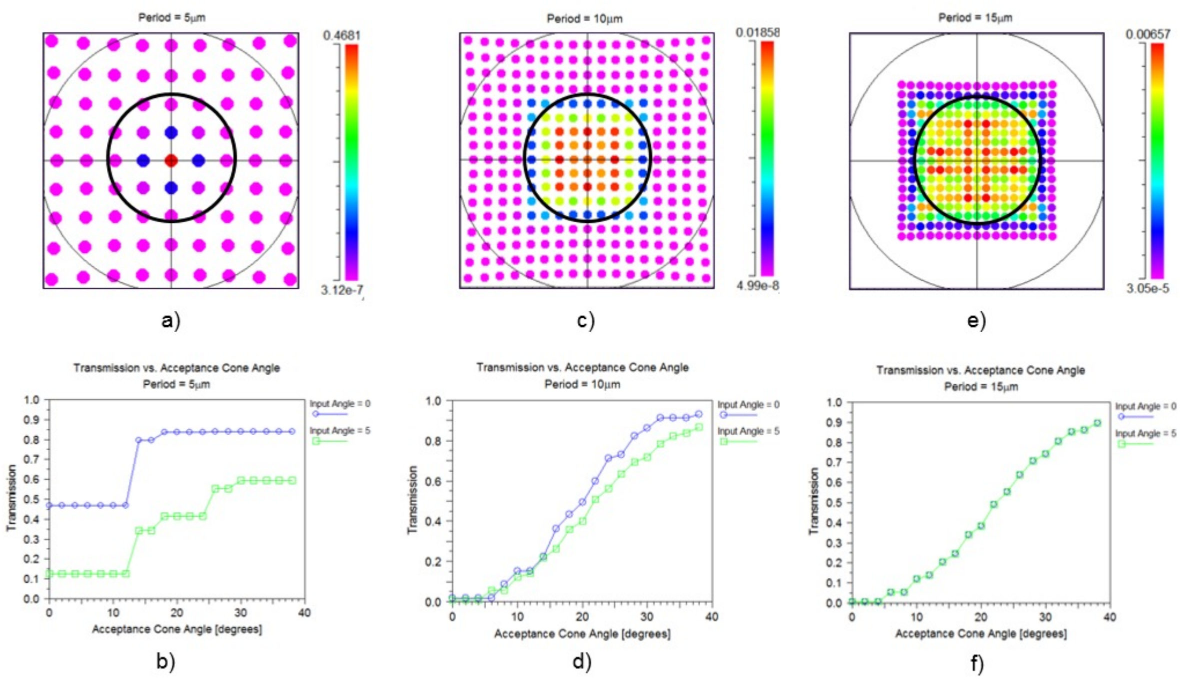

Figure 7. Transmitted diffraction orders (TDO) at discrete input angle of 0° and estimated efficiencies (EE) at two discrete input angles (0° and 5°) for various pixel sizes: a) TDO at Period = 5 µm, b) EE at Period = 5 µm, c) TDO at Period = 10 µm, d) EE at Period = 10um, e) TDO at Period = 15 µm, and f) EE at Period = 15 µm.

Figures 7(b), (d), and (f) show the estimated efficiency as a function of acceptance cone angle for the three pixel sizes studied at two discrete input angles (0° and 5°). Looking only at an input angle of 0°, it appears that a smaller pixel size is more efficient, specifically at lower acceptance cone angles. However, as the input angle increases, smaller pixel sizes quickly become less efficient. This further limits the range of input angles that the LC panel can effectively transmit which requires careful design of the illumination system.

4. MIXED-LEVEL SIMULATION

While EM simulation provides a detailed model of the LC panel, it cannot simulate the detailed effects of the illumination and/or lens systems, or the quality of projected image. Co-simulation using EM and RT methods is required. A polarimetric BSDF (Bi-Directional Scattering Distribution Function) file was calculated using RCWA and then used to define a surface property in the RT simulator. The BSDF database was generated for an input angular range of 0° to 10° at a spacing of 1° (angle measured from surface normal) and an azimuthal angular range of 0° to 360° with a spacing of 30°. The calculation took about ~1 hour using a workstation with 2 Xeon CPUs w/8 cores each, using a distributed scan with 4 simultaneous simulations. The polarimetric BSDF file was applied as a surface property in the RT geometry.

Figure 8 shows far-field patterns calculated by RT for various ranges of incident angles to emulate the projector illumination system. These results correspond to light incident on a standalone LC panel without an imaging system. Results for pixel sizes corresponding to Period = 10 µm and 5 µm are shown. The incident angular range and total transmitted power is noted for each plot. The transmitted diffraction orders blur and the total transmission is reduced as the incident angle spread widens. These results are consistent with the RCWA results: the angular spread of the transmitted orders gets smaller and the total transmitted power decreases as the pixel size decreases.

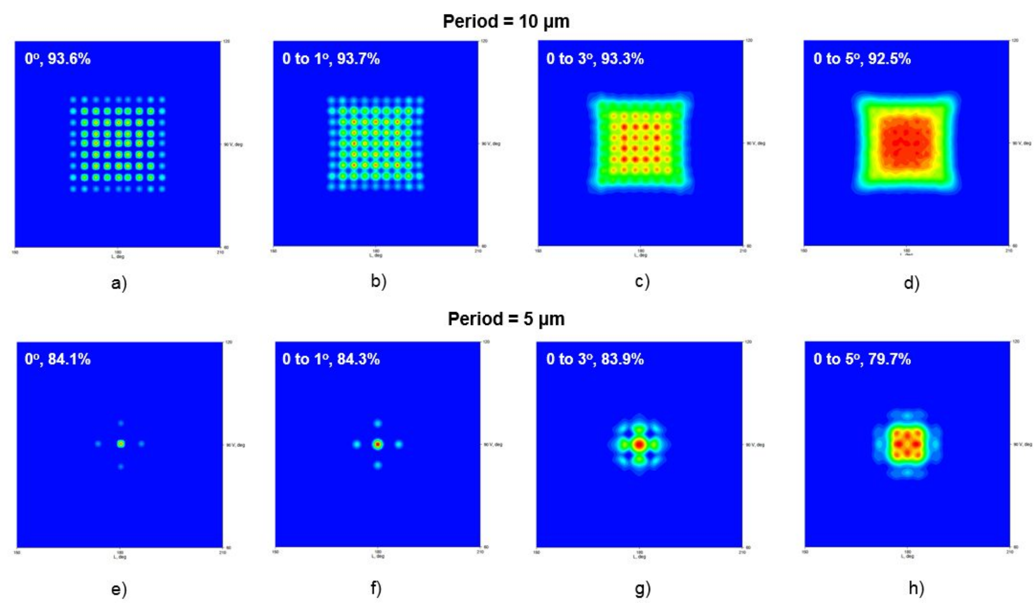

Figure 8. Far-field patterns calculated with RT for: a-d) Period = 10 µm and e-h) for Period = 5 µm. The angular spread and total transmitted power is noted for each plot.

Figure 9(a) shows the LC panel with an imaging system and simulated rays. The illumination system was emulated by using an incident angle range of 0° to 5° with a Lambertian angular spread. The LC panel size was such that it contained 1920 x 1080 pixels when using the polarimetric BSDF file corresponding to a pixel size of 10 µm. The imaging system was designed with an acceptance cone angle of 30°, which corresponds to f/1.8.

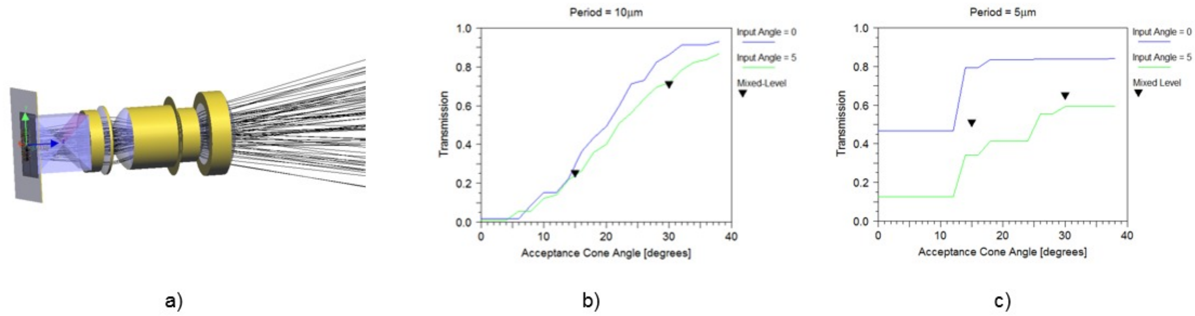

Figure 9. a) LC panel, imaging system, and simulated rays from the RT simulation, b) comparison of mixed-level results with estimated efficiency calculated by RCWA for a period of 10 µm, and c) comparison of mixed-level results with estimated efficiency calculated by RCWA for a period of 5 µm.

Figure 9(b) and (c) show a comparison of the estimated efficiency calculated by RCWA with the transmission simulated through mixed-level simulation for pixel sizes of 10 µm and 5 µm respectively. The two mixed-level results shown in Figure 9(b) and (c) correspond to the designed angular acceptance cone of the lens system (30°) as well as stopping the lens system down to 15°. The results from RCWA are at discrete input angles of 0° and 5°, whereas the mixed-level results have an incident angular range of 0° to 5° with a Lambertian angular spread. The mixed-level results are consistent with the results estimated with RCWA but are more rigorous since they take into account inefficiencies introduced by the imaging system that were not possible to model with RCWA or RT alone.

5. CONCLUSION

The presence of geometric features varying in size over orders of magnitude in projector designs require a variety of numerical techniques to optimize their design and analyze their performance. A mixed-level simulation methodology combining several of these techniques (RCWA, BSDF, and ray-tracing) has been used to model the performance of such a projector. RCWA was used to generate the polarimetric BSDF for the LC panel. This information was then incorporated into ray-tracing as a surface property which permits the overall analysis of the device performance. The results show that as the pixel size becomes smaller, the LC panel becomes more sensitive to the input angular range for the structure studied. Moreover, the diffractive nature of the LC panel should be taken into account when designing the imaging system to avoid efficiency loss. A mixed-level simulation approach that combines the strengths of EM and RT techniques is required to comprehensively model the optical characteristics of projectors.

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