Design of Diffractive Optical Elements for Augmented/Virtual Reality Applications

Simulation and Design Using RSoft Tools
Outline

• Introduction
• Synopsys Solutions for AR/VR
• Design Case 1 – Diffractive Slanted Grating
• Design Case 2 – DOE on planar waveguides
• Conclusion
Virtual Reality (VR)

- VR embeds our senses with a 3D, computer generated environment
- This environment can be interacted with and explored
Augmented Reality (AR)

• AR enhances your existing natural environment by overlaying virtual information on top of it

• Both worlds harmoniously exist, providing users a new and (hopefully!) improved natural world where virtual information can provide assistance to everyday tasks
VR and AR has potential to revolutionize many aspects of human life, and is projected to have extremely strong growth.
Optics is Key for VR/AR

• “Optics remains the key challenge in developing the ultimate virtual experience”

Bernard Kress, Microsoft’s Hololens Division @ SPIE Photonics West 2018:

• New types of optical and photonics technologies need to be implemented in next-generation VR/AR systems in order to achieve a better sense of display immersion for the user, and provide greater visual comfort for prolonged usage
AR/VR Requirements

• Main VR/AR requirements:
  – Low weight
  – Small Size
  – Insensitive to vibration
  – Comfortable

• Types of existing systems include:
  – Freeform optical prism projection system:
  – Retina scanning
  – Reflective systems or hybrid reflective/refractive systems
  – **Optical planar waveguides with diffraction gratings**
    – This system has potential to meet AR/VR design requirements
    – Synopsys tools can be used for the design process!
Basic Schematic of Optical Waveguide System

Near-Eye-Display (NED) Systems

- Functions of the Diffractive Gratings:
  - Couple light into waveguide plate and couple light out of plate into eyes
  - Wavelength selection
  - Wavefront reshaping
- Gratings must be designed properly so that the optical system produces good images
Analyzing Gratings using Diffraction Theory

- k vector of incoming light:
  \[ k_i = \frac{2\pi}{\lambda} n_0 (\sin \theta_0 \cos \varphi_0, \sin \theta_0 \sin \varphi_0, \cos \theta_0) \]

- k vector of \( A = m^{th} \) diffraction order inside the waveguide:
  \[ k_m = \frac{2\pi}{\lambda} n_1 (\sin \theta_m' \cos \varphi_m', \sin \theta_m' \sin \varphi_m', \cos \theta_m') \]

- From the grating equations in conical geometry:
  \[ n_1 \sin \theta_m' \sin \varphi_m' = n_0 \sin \theta_0 \sin \varphi_0 = \gamma \]
  \[ n_1 \sin \theta_m' \cos \varphi_m' = n_0 \sin \theta_0 \cos \varphi_0 + m \frac{\lambda}{T} = \alpha_1 + m \frac{\lambda}{T} \]

- Assuming the 1\(^{st}\) order must TIR in the waveguide, the largest period that we can use is given by:
  \[ T < \frac{\lambda}{\sqrt{1-\gamma^2} - \alpha_0} \]
Analyzing Gratings using Diffraction Theory

• Furthermore, consider the requirement that there are no orders higher than the +/-1 order, the waveguide indexes are bounded by:

\[
\sqrt{\gamma^2 + \left[ \frac{\alpha_0 + \frac{2\lambda}{T}}{2} \right]^2} > n_1 > \sqrt{\gamma^2 + \left[ \frac{\alpha_0 + \frac{\lambda}{T}}{2} \right]^2}
\]

• This simplistic approach is not enough, the actual grating geometry must be optimized to achieve a realistic grating that works in real operating conditions. This includes:
  – Period
  – Diffraction Angle of each order
  – Diffraction efficiency of each order
  – Grating materials and geometry
  – Others…

Plate Index \(< n <\)
Synopsys Solutions for AR/VR
Synopsys’s Solution for AR/VR Optical System Design

- **Optical System**: Synopsys LightTools
- **Grating Design**: Synopsys RSoft
  - RSoft CAD / DiffractMOD / FullWAVE / MOST Optimizer
DiffractMOD: RSoft’s RCWA tool

• DiffractMOD is a very efficient tool to rigorously calculate diffraction properties of transversely periodic devices

• DiffractMOD outputs:
  – Reflection/Transmission power for each diffraction order
  – Total reflection/transmission
  – Amplitude/Phase/Angle for each diffraction order
  – Field distribution in simulation domain
RSoft and LightTools Co-Simulation

• RSoft Component Tools
  – Based on physical optics
  – Maxwell’s equations, etc
  – Small photonics devices
  – Wave propagation and multi-physics
  – Diffraction, polarization, nonlinearity, electro-optical, thermo-optics, etc.

• LightTools
  – Based on geometrical optics
  – Snell’s law, etc.
  – Large bulk optical system
  – Ray tracing and beam propagation
  – Reflection, refraction, diffraction

Feature Size vs. Wavelength

LaserMOD  FullWAVE  BeamPROP  DiffractMOD
Smaller...

Physical optics  ~10\(\lambda\)  Geometrical optics
RSoft

LightTools  CODE V
Larger (> ~10 \(\lambda\))
RSoft/LightTools BSDF Interface

• RSoft BSDF files:
  – Automatically calculated using RSoft’s FullWAVE or DiffractMOD packages
  – Contains information about how a surface (thin film, patterns, etc.) scatters light
  – Reflection/transmission data is stored for illumination from both sides of the surface
  – Scatter information is stored as a function of two incident angles, wavelength, and polarization

• The RSoft BSDF file is then used in LightTools to define a surface property
  – Rays that hit the surface in LightTools are ‘diffracted’ according to the data in the RSoft BSDF file
Design Case 1 – Diffractive Slanted Grating
Design Case 1: Structure Overview

- Diffractive slanted gratings are manufactured onto a high refractive index plastic waveguide with simple UV replication technology. Large quantity manufacturing is possible.

- The slanted gratings can be optimized to have high 1st order transmission efficient for right in-coupling and high -1st order transmission efficient for left in-coupling (> 92%).

- Two types of slanted gratings for out-coupler. The efficiency can be optimized as well.

T Levola et al, “Replicated slanted gratings with a high refractive index material for in and outcoupling of light”, Optics Express, 15 (2007)
Using DiffractMOD for Grating Design

- **Grating Properties:**
  - **Wavelength:** 0.52 µm
  - **Period:** 0.405 µm
  - **H**: grating height
  - **A**: slant angle
  - **L**: Left slope angle from slant axis
  - **R**: right slope angle from slant axis
  - **Fill**: duty ratio
  - **Index**: 1.716
Simulation Results

Reflection vs. Transmission Type Gratings
- RSof MOST scanner is a very powerful tool to investigate structure parameters.

- In this case, maximum power in the +1 (right in-coupler) and -1 (left in-coupler) are desired.
Finding Optimal Structure with MOST Optimizer

- MOST Optimizer uses a genetic algorithm to explore the parameter space.
- A Python function was used to maximize the power in the -1 order.
- The geometry for the starting point and final optimal point are shown.

Target Function (Python)

```python
# Target Function

def get_de(array, x, y):
    # Find X/Y size of array (requires odd size)
    xorders = array.shape[0] - 1
    yorders = array.shape[1] - 1
    if (xorders + yorders) % 2 == 0:
        return de_for_x_y_order_from_array(x, y, xorders, yorders)
    else:
        yorders -= 1

# Example usage

# de_0, de_1, de_2 are the target functions

# Get de for x, y order from array

# Show the Transmitted Diffraction Efficiency vs. Angle graph
```

Optimizer finds a structure that meets the target function.
RSoft BSDF Calculation for Optimal Structure

- Angular range of RSoft BSDF file:
  - **Phi** (from normal): Range of [0,90] with 1° spacing
  - **Theta** (around normal): Range of [0,360] since the structure is anisotropic with 5° spacing

- BSDF Utility runs DiffractMOD simulations and both polarizations are automatically calculated
Using RSoft BSDF files in LightTools

- RSoft BSDF files were calculated for each grating and assigned to the appropriate LightTools surface.

- Test rays were used to verify that the basic design worked.
LightTools/RSoft Co-Simulation Results

• A patterned hole array was used as a test image; the hole array image is clearly seen at both eyes

• The incident source has an angular spread of 13° while the grating was designed for collimated input

• The angular sensitivity of the grating can be explored to improve the uniformity of the device

• Possible improvements include:
  – Combined optimization of diffraction gratings
  – Free form optical systems
Design Case 2 – DOE on planar waveguides

By: Tung Yu Su, Cybernet System Taiwan
Design Case 2: Structure Overview

- Three grating groups will be included in this VR/AR system:
  - **Input Grating**: Used to couple light into a substrate, diffracting light at an angle and making light propagate in the substrate by total reflection
  - **Diffractive Exit Pupil Expander (EPE) Grating**: Used to expand the light
  - **Output Grating**: Used to couple out the light from a substrate into air, guiding the light into other optics in the system

Diffractive Exit Pupil Expander (EPE)

• The size of the waveguide structure can be minimized using a simple virtual image generator having a small exit pupil and an exit pupil expander (EPE)

• Here, we use an even number of first-order diffractions, which contains an input grating, an output grating, and a diffractive EPE to expand a single input beam to a 4 x 4 beam array in a very thin optical waveguide
• The prototype for the input grating is a ‘line grating’ since a single etch process can be used since the height of every fin is the same.

• Requirements for input grating:
  – Transmitted diffractive angle must be larger than the total reflection angle (TIR)
  – Transmission should be more than 70% for the incident angle range ±15°

• Structural Parameters:
  – Period (fixed to meet requirement of output diffractive angle)
  – Width
  – Height
  – Filling Factor
  – Index/Material
MOST Optimization

• Before performing a successful optimization, a suitable error function should be clearly defined:
  – The target of this optimization is the ‘uniformity’ of transmitted power
  – The blue line (uniformity before optimization) should move towards the red line (target)

• A Simplex algorithm was chosen for this optimization study
Optimization of Input Grating

- Optimization details:
  - 150 steps (1583 simulations) were performed to find a converged result
  - 31 models were automatically saved during optimization; users are able to check the performance of every model

- Result shows increased transmitted power across $\pm15^\circ$ incident angular range, >70%
Output Grating

• The output powers of “Out1”, “Out2”, “Out3” and “Out4” should be close to each other, keeping a good output power uniformity
• To achieve this target, a single grating is not sufficient: the Output area is divided into four areas
  – Each area has a different grating
  – Output power(s) can be properly designed

Beam width = 3.5 mm
W=1.5mm
## Output Gratings

<table>
<thead>
<tr>
<th></th>
<th>Grating1</th>
<th>Grating2</th>
<th>Grating3</th>
<th>Grating4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Power</strong></td>
<td>1</td>
<td>0.75</td>
<td>0.5025</td>
<td>0.25025</td>
</tr>
<tr>
<td><strong>Diffraction Efficiency</strong></td>
<td>25%</td>
<td>33%</td>
<td>49.8%</td>
<td>99%</td>
</tr>
<tr>
<td><strong>Output Power for -1&lt;sup&gt;st&lt;/sup&gt;</strong></td>
<td>0.25</td>
<td>0.2475</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Power to the next area</strong></td>
<td>0.75</td>
<td>0.5025</td>
<td>0.25025</td>
<td>0</td>
</tr>
</tbody>
</table>

- Goal: 25% of power output in each area which means that the -1<sup>st</sup> order must have different output power for each grating

- Here we fix these parameters of the four gratings:
  - Height (so only one mask is needed)
  - Material
  - Period

- Multi-variable optimization is needed again!
Optimizations of Output Gratings

• Error functions are easy to define in RSoft’s MOST:

• Optimized models can be checked after optimization, geometry is shown here:
Gratings for EPE

- The design of the EPE includes the second incident angle (theta)
- The grating was designed to split the light as shown below
Gratings for EPE

- RSoft’s DiffractMOD, a 3D full-vector RCWA-based simulator, allows users to freely change the incident conditions such as angle, polarization, or phase.
  - For a fixed launch angle ($\varphi=53.9^\circ$), a theta scan can be performed to find optimal transmission/reflection:
Optical System in LightTools

- RSoft BSDF files for each grating were used to define the surface properties of the appropriate area in LightTools:
  - Users are able to rotate the axes of optical properties to achieve the tilted grating profile.
Optical System in LightTools

- Data in the output plane shows 16 beams after propagating through the input grating, EPE grating and four output gratings
  - One beam is coupled into substrate
  - 4 beams are generated by EPE
  - 16 beams are coupled out
- Uniformity of the output beams can be further improved by optimizing the EPE grating
Conclusion

• Synopsys provides a complete set of tools to study AR/VR devices

• Workflow:
  – RSoft (grating design and optimization) → BSDF interface → LightTools (optics systems design)

  ✓ Build gratings in RSoft CAD
  ✓ Build merit function for optimization
  ✓ Optimize gratings in RSoft MOST
  ✓ Examine performance
  ✓ Export BSDF files by BSDF Utility

  ✓ Set up a UDOP with RS-LT interface (.dll), and load the BSDF files generated by RSoft
  ✓ Build optics in LightTools
  ✓ Evaluate optical performance in LightTools

• Design and Optimization of Gratings:
  – Gratings can be optimized based on diffraction angle, efficiencies, etc. of any order or combination of orders
  – MOST Optimization in RSoft CAD provides a convenient method to optimize gratings with either FullWAVE or DiffractMOD

• Data Processing:
  – No extra work to use RSoft BSDF data in Synopsys' LightTools
  – All diffractive properties are included in the RSoft BSDF files, including R/T, dispersion, polarization, etc

• Manufacture:
  – Users are able to export layout files from RSoft directly, and manufacture gratings in a suitable process