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.
Estimated VR/AR Market

- 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:

\[ k_i = \frac{2\pi}{\lambda} \left( \sin \theta_i \cos \varphi_i, \sin \theta_i \sin \varphi_i, \cos \theta_i \right), \]

• k vector of \( A = m^{th} \) diffraction order inside the waveguide:

\[ k_m = \frac{2\pi}{\lambda} \left( \sin \theta'_m \cos \varphi'_m, \sin \theta'_m \sin \varphi'_m, \cos \theta'_m \right), \]

• From the grating equations in conical geometry:

\[ n_i \sin \theta'_m \sin \varphi'_m = n_i \sin \theta_i \sin \varphi_i = \gamma \]

\[ n_i \sin \theta'_m \cos \varphi'_m = n_i \sin \theta_i \cos \varphi_i + m \frac{\lambda}{T} - \alpha_i + m \frac{\lambda}{T} \]

• Assuming the 1\textsuperscript{st} order must TIR in the waveguide, the largest period that we can use is given by:

\[ T < \frac{\lambda}{\sqrt{1 - \gamma^2} - \alpha_i} \]
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:

\[
\sqrt{\gamma^2 + \left( \alpha_0 + \frac{2\lambda}{T} \right)^2} > \lambda_1 > \sqrt{\gamma^2 + \left( \alpha_0 + \frac{\lambda}{T} \right)^2}
\]

• 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**

- Smaller...
- **~10λ**
- Larger (> ~10 λ)

---

**RSoft**
- LaserMOD
- FullWAVE
- BeamPROP
- DiffractMOD

**LightTools**
- CODE V
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 1\textsuperscript{st} order transmission efficient for right in-coupling and high -1\textsuperscript{st} order transmission efficient for left in-coupling (> 92%).

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

---

T Levoja 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

- **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
Exploring Parameter Space with MOST Scanner

• RSoft 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)

def d(m, net, measurements, Systab, extras):
    # Python function for metric
    #
    # # read R/T order measurements
    # # r_orders = measurements["r_orders"].data()
    # t_orders = measurements["t_orders"].data()
    #
    # # print r_orders
    # # print t_orders
    #
    # metric
    # err0 = abs(1. - get_d,(t_orders,-1,0))
    # ans = err0
    # print 'Error: ', ans
    # print 'Returning: ', ans
    # return ans

# HELFUL FUNCTIONS

def get_d(array, x, y):
    # return d for x,y order from array'
    # find X/Y size of array (requires odd size)
    # xorders = array.size[0] - 1)
    # order = (array.shape[0] - 1)/2
    #
    # else:
    #
```

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

- **Angular range of RSoft BSDF file:**
  - \textit{Phi} (from normal): Range of [0,90] with 1° spacing
  - \textit{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 a input grating, a 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 ±15° incident angular range, >70%
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
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 -1st</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 -1st 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:

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Indep. vars</th>
<th>Measurements</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metric: scalars derived from measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{Expression: } (0.75 - \text{dm}_0 \cdot \text{t}_0 \cdot \text{r}_0 \cdot \text{Single})^2 + (0.25 - \text{dm}_1 \cdot \text{t}_0 \cdot \text{r}_1 \cdot \text{Single})^2
\]

• 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 ($\phi=53.9^\circ$), 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

  BSDF Interface

• 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