Design and Optimization Strategy of Coupling Gratings for Near-Eye Displays

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- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects
"AR I think is going to become really big," said Cook. "VR, I think, is not gonna be that big, compared to AR ... How long will it take? AR gonna take a little while, because there’s some really hard technology challenges there. But it will happen. It will happen in a big way. And we will wonder, when it does [happen], how we lived without it. Kind of how we wonder how we lived without our [smartphones] today."
Tim Cook on AR Glasses

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• “But today I can tell you the technology itself doesn’t exist to do that in a quality way. The display technology required, as well as putting enough stuff around your face – there’s huge challenges with that.”

• “The field of view, the quality of the display itself, it’s not there yet,” he says. And as with all of its products, Apple will only ship something if it feels it can do it “in a quality way”.

https://www.independent.co.uk/life-style/gadgets-and-tech/features/
Typical Imaging Unit

- Panel source
- Human eye
- Retina
Typical Additions to Basic Setup

- Panel source
- F-Theta lens
- Light Guiding Apparatus
- Human eye
One option for such light guiding via thin structures is a lightguide.
An accurate modeling of the coupling and guiding of the FOV modes requires a fast physical optics modeling concept!
Non-Sequential Light Propagation

Lightguide simulations require a good non-sequential light propagation capability!

Guiding by total internal reflection (TIR)
Lightguide Coupling Approach

How to achieve an efficient coupling of a set of field of view modes into a lightguide?
**Lightguide Coupling Approach**

**Workflow:**
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides
2. Designing the structure profile of the incoupling grating by an optimization approach

- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis
Lightguide Coupling Approach

Workflow:
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides
2. Designing the structure profile of the incoupling grating by an optimization approach
Mathematical Modeling: Direction Vector and $k$-Domain

- Field of View (FOV) angles denoted by the Cartesian angles $\theta_x$ and $\theta_y$.
- This defines a unit direction vector according to

$$\hat{s} \overset{\text{def}}{=} \frac{(\tan \theta_x, \tan \theta_y, 1)}{\sqrt{1 + \tan^2 \theta_x + \tan^2 \theta_y}}$$

- The vector $k$ of a plane wave is defined by

$$k = k_0 n \hat{s},$$

with $k_0 = 2\pi/\lambda$ and the refractive index $n$ of the medium in which we consider the wave.
Mathematical Modeling: k-Domain Consideration

The consideration of the coupling and guiding situation of the FOV modes in the spatial frequency domain is much more convenient than in the space or angular domain!

\[ \kappa^{lg} = k_0 n^{lg} s_{in}^{lg} \]

\[ \kappa^{in} = k_0 n^{air} s_{in}^{air} \]

Calculated by FOV angle \((\theta_x, \theta_y)\)
A guided mode must be a propagating mode

\[ \kappa_{\text{lg}} \leq k_0 n_{\text{lg}} \]

Calculated by FOV angle \((\theta_x, \theta_y)\)
Furthermore, the guided mode must fulfill the total internal reflection condition to propagate without any losses.

\[ \kappa_{\text{lg}} \geq k_0 n_{\text{air}} \]

Mathematical Modeling: TIR Condition

total internal reflection (TIR) limit

\[ \kappa_{\text{lg}} = k_0 n_{\text{lg}} s_{\text{in}}^{\perp} \]

\[ \kappa_{\text{in}} = k_0 n_{\text{air}} s_{\text{in}}^{\perp} \]
These both condition lead to the guiding condition of lightguides

\[ k_0 n^{lg} \geq |\kappa^{lg}| \geq k_0 n^{air} \]

How to shift (deflect) the modes?
A grating is an elegant component for the coupling because the FOV is shifted in the k-domain under consideration of the grating vector $\mathbf{G}$.

\[ k_0 n_{\text{lg}} \geq |\kappa^{\text{in}} + m \mathbf{G}| \geq k_0 n_{\text{air}} \]

In general, the 2D-periodic grating vector has two components

\[ \mathbf{G} = \left( \frac{2\pi}{p_x}, \frac{2\pi}{p_y} \right)^T \]

with period along the x- and y-axis ($p_x, p_y$) and the diffraction order $\mathbf{m} = (m_x, m_y)^T$. 
• In case of 1D-periodic gratings one component of the grating vector becomes zero, so that $G_y = 0$ without loosing of generality.

• From that follows the range of the period of a 1D-periodic grating geometry to couple a certain FOV into a lightguide:

$$\frac{2\pi}{\sqrt{(k_0 n_{\text{air}})^2 - (k_y^{\text{in}})^2 - k_x^{\text{in}}}} \geq p \geq \frac{2\pi}{\sqrt{(k_0 n_{\text{lg}})^2 - (k_y^{\text{in}})^2 - k_x^{\text{in}}}}.$$
Optimization Task

How to design a binary grating structure to couple a set of plane waves into a planar lightguide?

Workflow:
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides
2. Designing the structure profile of the incoupling grating by an optimization approach

set of plane waves
- field of view (-15..15, -10..10)°
- wavelength 532nm
- linearly polarized along x-axis

grating efficiencies detector

1st diffraction order
Simulation Results and Configuration of the Merit Function

**Inputs**
- variation of the fill factor $c/p$ with the slit width $c$ and the period $p$
  - 0.1% to 99.9%
- variation of the modulation depth $h$
  - 50nm to 1500nm

**Initial Configuration of Grating**
- fill factor: 50.00%
- modulation depth: 400.00nm
- period: 410nm
- operating order: 1st transmitted

**Detector Result: Grating Efficiencies**
- Mean Efficiency 10.96%
- Uniformity Contrast 89.45%

**Angular Efficiency Plot [%]**

A roughly sampled evaluation of the incidence angles along the period is sufficient for the optimization.

**to be varied**
the following optimization workflow is applied to design a binary grating for efficient lightguide coupling:

1. Define the inputs and their ranges, start with a reference input combination
2. Perform the optimization with several simulations
3. Calculate the corresponding outputs
4. Evaluation of the defined objectives
5. Next iteration with new inputs

the optimization algorithm stops after certain iterations and/or when no more improvement of the objectives can be achieved
Optimization Results of optiSLang

- The optimization results are plotted as a function of the merit functions:
  - mean efficiency
  - uniformity contrast

- The Pareto front indicates the optimum compromise between the two merit functions (highlighted).

- Any optimization result at the Pareto front might be selected depending on the needs of the optical designer.
Advanced Evaluation of the Optimization Results

- for a better understanding how the input parameters are correlated to the output parameters, the Pareto front designs are visualized in a *Parallel Coordinates Plot* (1)
- in addition, a cluster analysis is performed to group a specific parameter (e.g. relative slit width) into colored clusters for highlighting the relationship of the input parameters to the output parameters
- for example, a low modulation depth and a low relative slit width (red cluster) lead to the best uniformity contrasts but to poor mean efficiencies on the other side
- furthermore, the same colors are visualized on the Pareto front (2) to visualize the clusters (here: the impact of the slit width on both objectives)
- therefrom, the optical designer is able to select a robust design with the best compromise between the input parameters and the output parameters
Advanced Evaluation of the Optimization Results

- as a result, a design is selected, which is the best compromise for a prioritized low uniformity contrast and an acceptable mean efficiency including manufacturable grating parameters

- the *Parallel Coordinates Plot* illustrates the corresponding input parameter combination for this design (black curve)
finally, the optimization result is analyzed regarding the coupling efficiency using the software VirtualLab Fusion.

as a result, the uniformity contrast was significantly reduced but to the cost of the entire efficiency.
Optimization Task

How to design a slanted grating structure to couple a set of plane waves into a planar lightguide?

Workflow:
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides

2. Designing the structure profile of the incoupling grating by an optimization approach

- field of view (-30..30, -15..15°)
- wavelength 532nm
- linearly polarized along x-axis
Optimization Result of optiSLang

- an evolutionary optimization algorithm is applied using the optimization software optiSLang
- the additional freedom of the slant angle provides additional solutions

solution space of varying modulation depth and fill factor

additional solution space due to slant angle variation
Analysis of Coupling Efficiency for Optimization Results

- an appropriate solution can be selected according specific constraints
- either uniformity contrast or mean efficiency might be prioritized

Mean Efficiency 58.74%
Uniformity Contrast 89.49%

Mean Efficiency 10.34%
Uniformity Contrast 15.51%

- fill factor 70.82%
- modulation depth 381.91 nm
- slant Angle 24.58°

- fill factor 90.00%
- modulation depth 189.64 nm
- slant Angle 14.57°
Conclusion

Inputs
- fill factor
- modulation depth

Objectives (merits)
- maximize mean efficiency
- minimize uniformity error

Simulation
- simulation of the lightguide coupling using the software VirtualLab Fusion

Outputs
- mean efficiency
- uniformity contrast

- VirtualLab Fusion interconnects various field tracing solvers to enable fast physical optics modeling
- optiSLang is a software for sensitivity analysis, multiobjective and multidisciplinary optimization, robustness evaluation, reliability analysis and robust design optimization
- both were used for the design of an optical grating to couple an FOV field into a planar lightguide setup for AR&VR applications
Thank you for your attention!