Towards Estimating Diffractive Sidewall Scattering Losses for Light Pipes

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INTRODUCTION: The impact of surface roughness on the optical transmission of light pipes has been addressed using a geometric optics approximation (GOA) [1]; however, a basic estimate for diffractive losses remains to be included. Using COMSOL®, we compare 2D Wave Optic Simulations for diffractive efficiencies to those predicted by nonparaxial scalar theory [2] for sinusoidal phase gratings.

Glass light pipes have been fabricated using femtosecond laser irradiation followed by chemical etching. After etching, the surfaces are rough and may require subsequent polishing to achieve optical quality smoothness. The degree of smoothness will impact the transmission, so simulation work aims to understand the tradeoffs in surface roughness parameters and induced loss. While rough surfaces can be simulated (as shown in Fig. 1) and modeled directly, Wave Optics solutions are time consuming and solutions are needed over a large ensemble of surfaces. Our goal is to modify the GOA estimate to include diffractive effects on each ray-interface (core-to-cladding) intersection.

COMPUTATIONAL METHODS: An important metric for estimating sidewall scattering loss under the GOA is the local RMS surface slope [1]. The RMS slope can be calculated for random and deterministic surfaces. For a sinusoid with period d and peak-to-valley height h, the RMS slope is denoted by m_s:

$$m_s = \frac{\pi}{\sqrt{2}} \frac{\hat{h}}{\hat{d}} \quad \text{where}$$

$$\hat{h} = \frac{h}{\lambda}, \text{ and } \hat{d} = \frac{d}{\lambda}$$

Figure 1. Rectangular cuboid light pipe (1mm^{2}x10mm) with rough surfaces and ray simulation.

Harvey's [2] nonparaxial scalar diffraction theory is compared to the wave optics simulation results for TE. The efficiency η_m into each order, which is normalized to the sum of diffracted efficiencies, is calculated in Matlab using the following equations:

$$\frac{\text{a}}{2} \cong \pi\hat{h}\left[\cos(\theta_i) + \cos(\theta_m)\right]$$

$$\eta_m \cong \frac{J_m^2\left(\frac{a}{2}\right)}{\sum_{m=min}^{max} J_m^2\left(\frac{a}{2}\right)}$$

RESULTS: A single core-to-cladding interface is simulated, e.g. n_1=1.46 and n_2=1.0, using the Wave Optics Module (2D simulation, TE-polarization) to calculate the diffraction order efficiencies for a range of parameters. An example is shown in Fig. 2 for a free space wavelength of 550nm and m_s=0.0444.

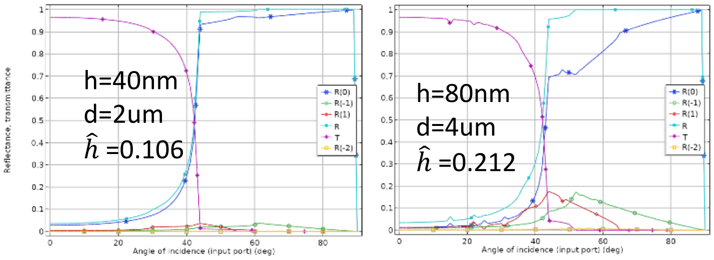

Figure 2. Wave optics simulation for sinusoidal 2D surface at a glass-air interface, showing the 0th and first diffraction orders for reflection.

Example nonparaxial scalar calculations are shown in Fig. 3 for different values of $\hat{h}$, but with the same slope.

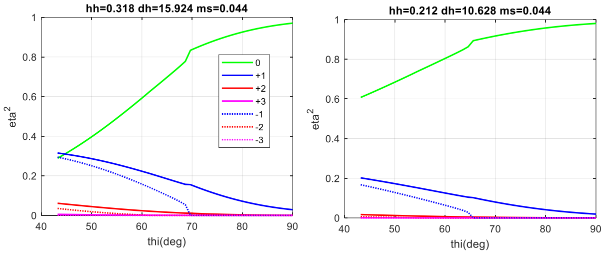

Figure 3. Nonparaxial scalar diffraction calculations (hh= $\hat{h}$, dh= $\hat{d}$), neglecting Fresnel reflection losses.

The efficiency for each order was multiplied by a Fresnel loss term, $\sqrt{R(\theta_0)R(\theta_m)}$, and the 0th-order re-normalized to achieve the best fit to the Wave Optics results in Fig. 4.

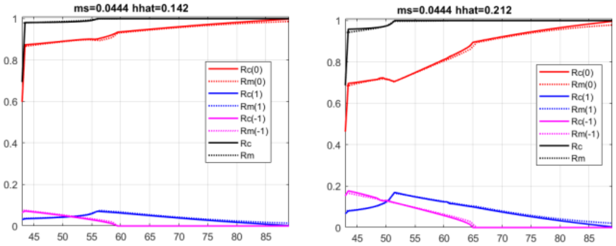

Figure 4. Comparison of Wave Optics and nonparaxial scalar diffraction estimations. Subscipts: c=Comsol, m=Matlab.

CONCLUSIONS: Insight into the diffractive effects at a dielectric interface is gained by simulating a sinusoidal phase grating. This enabled a quantitative comparison to nonparaxial scalar diffraction calculations. The latter provides a simple approach for estimating the diffractive effects for light pipe sidewall scattering.

REFERENCES:

1. Madsen and Hu, "Empirical Model for Estimating Light Pipe Sidewall Scattering Loss," OSA FiO+LS Conference, JW6A.12, 2020.
2. Harvey and Pfisterer, "Understanding diffraction grating behavior: including conical diffraction and Rayleigh anomalies from transmission gratings", Optical Engineering, 58(8), 087105, 2019.

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