# Waveguide Grating Couplers in Overlaid Chips: Efficiency Optimization and Angular Misalignment Simulation

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**Abstract:** Applying reflectors adds 30%~40% to the diffraction efficiencies of binary waveguide gratings. The greatest angular misalignment sensitivity occurs for rotations about the grating groove axis and rotation should be limited to ±3°.

**OCIS codes:** (050.1950) Diffraction gratings; (050.1960) Diffraction theory; (060.1810) Buffers, couplers, routers, switches, and multiplexers.

## 1. Introduction

A number of optical interconnect solutions have been proposed to achieve compact, high-bandwidth integrated systems. As more optical components are integrated into 2.5D/3D multilayer platforms, out-of-plane interlayer optical connectors, such as 45° mirrors [1], evanescent couplers [2], and diffraction gratings [3], are necessary elements to couple optical signals into and out of waveguides on overlaid chips. Diffraction gratings are promising optical couplers with planar geometry which are compatible with wafer-scale manufacturing and testing. Improving the coupling efficiency of grating couplers is essential to minimize the power loss. Other than engineering the grating profile, a common method to increase efficiency is to incorporate reflectors, e.g. DBRs [4], double corrugations [5], or metal layers [6], to recycle the backward-diffracted light. Although grating structures can be optimized for specific coupling configurations, misalignment of overlaid chips is unavoidable due to fabrication and assembly tolerances. The ability to analyze misalignment effects and understand the underlying mechanism is thus needed to design grating couplers so that they are misalignment tolerant.

We have introduced a simulation tool, the rigorous coupled-wave analysis – equivalent-index-slab (RCWA-EIS) method, to optimize grating couplers with/without reflectors in perfectly aligned configurations as well as to analyze the angular misalignment effects on the coupling efficiency. To our knowledge, this model offers the first angular misalignment analysis for interlayer waveguide grating coupling. The simulation results compare favorably with FDTD calculations. The optimization of gratings with various profiles was introduced in our previous work [7,8]. In this paper, we present the effects of adding reflectors and angular misalignment.

## 2. Simulation model

Binary gratings consisting of cover, grating, waveguide and substrate are considered here. The interlayer coupling efficiency $\eta$ is approximated as the product of the top- and bottom-grating diffraction efficiency ($\eta \approx DE_t \times DE_b$). If the two gratings are designed to be identical, $\eta$ can be approximated as $\eta \approx DE_b^2$. For a given grating, the diffraction efficiency of +1th order into the cover $DE_b$ is optimized. One important step in the simulation is replacing the grating layer with multiple "equivalent index slabs" while retaining the field profiles outside of the grating [7,8].

2.1 Binary gratings with reflectors

Gratings with symmetric profiles have approximately half of the out-diffracted power travelling into the substrate, and thus it is efficient to recycle the downward-diffracted light using a reflector. Two types of reflectors are considered, namely grating reflectors and metal reflectors (Fig. 1). The RCWA-EIS formulation remains the same except for the addition of more layers corresponding to the reflectors. The grating reflector is replaced by equivalent index slabs, while the metal layer is treated as a uniform layer with negative real and positive imaginary relative permittivity, e.g. for gold, $\varepsilon_r = -112.68+j6.852$ at 1.55 μm wavelength. The reflectors are added to several optimized binary gratings. To optimize the reflector structure, three parameters, namely the buried oxide layer (BOX) thickness ($d$), grating reflector thickness ($t_{bg}$), and the horizontal shift of the grating reflector relative to the optimized binary grating ($\Delta x$), are set as unknowns for the case of grating reflector, whereas two parameters, namely the BOX thickness ($d$) and metal layer thickness ($t_m$), are set as unknowns for the case of metal reflector.

2.2 Angular misalignment analysis

The general 3D interlayer grating coupling configuration is depicted in Fig. 2. The bottom grating is rotated relative to the top grating. A guided wave is launched into the top waveguide along the $-x_t$ direction and out-diffracted from the top grating, and it is then incident conically onto the bottom grating. The simulation model is based on 3D-RCWA and RCWA-EIS methods [9] and it is capable of analyzing arbitrary angular misalignments.

## 3. Simulation results

For reflector optimizations, given parameters are $t_g$ = 0.2679 μm, $\Lambda$ = 0.6696 μm, and $\theta_c$ = 0.1002 rad; for angular misalignment analysis, given parameters are $t_g$ = 0.3249 μm, $\Lambda$ = 0.6477 μm, and $\theta_c$ = 0.2021 rad. Other parameters are given in Fig. 1.

3.1 Binary grating with reflector

Optimized parameters found for the grating reflector were $\Lambda_{bg} = \Lambda$, $t_{bg}$ = 0.3068 μm, $d$ = 0.2202 μm, and $\Delta x$ = 0.2962 μm; optimized parameters found for the metal reflector were $t_m$ = 0.5102 μm, and $d$ = 1.021 μm. Figure 3 shows the single grating diffraction efficiency ($DE_b$) as a function of the number of grating periods ($N$) for the basic grating with/without the reflector. From RCWA-EIS results, applying the grating reflector adds 30% in DE at a particular $N$ (e.g. DE increases from 50% to 80% at $N$=50), and applying the metal reflector adds 40% in DE (e.g. DE increases from 50% to 90% at $N$=50). Mismatch in FDTD and RCWA-EIS data is due to geometric issue; that is, RCWA assumes infinite long gratings, while FDTD simulates gratings with real lengths. Metal reflectors have been experimentally demonstrated by Kang *et al.* [5] and they achieved 40% increase in DE.

3.2 Angular misalignment analysis

To determine the effect of rotation on the coupling efficiency, the bottom grating is rotated about the $x_t$ axis, the $z_t$ axis, and the vector [2 2 1]. Figure 4 shows $DE_b$ as a function of rotation angle ($\delta$) for the three rotation schemes. Rotation about the $x_t$ and $z_t$ axis has less effect on DE than rotation about [2 2 1]. This is because the vector [2 2 1] has a relatively large y component. Rotation about the groove direction (y axis) produces the largest deviation from the Bragg condition and DE is correspondingly reduced. As a result, system designers should try to align the grating such that there is minimal rotation about the y axis, e.g. rotation should be limited to ±3° to achieve less than 10% change in DE.

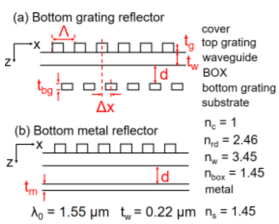


Figure 1: Schematics of two types of reflectors.

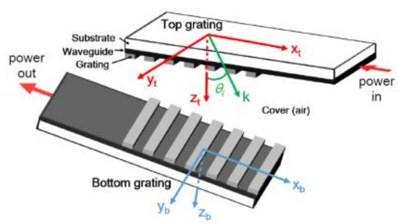


Figure 2: Schematics of 3D interlayer grating coupling.

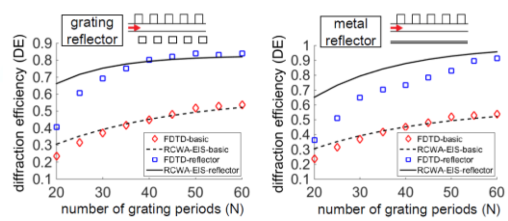


Figure 3: DE vs. N curves show significant increase in DE with reflectors.

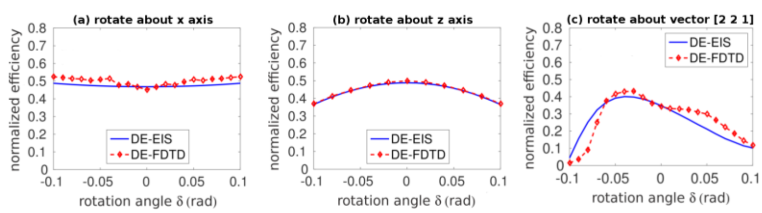


Figure 4: Bottom grating diffraction efficiency as a function of rotation angle. For (a) and (b), $N$ = 50; for (c), $N$ = 30 (shorter grating).

## 4. Conclusions

1) Applying grating or metal reflectors adds 30% or 40% to the diffraction efficiencies of waveguide gratings. 2) Angular misalignment of interlayer waveguide grating coupling is analyzed for the first time, and diffraction efficiency is less sensitive to the rotation about the x or z axis but greatly affected by the rotation about the y axis. 3) The simulation tool is computationally more efficient than FDTD or FEM calculations, e.g. seconds versus days.

## 5. References

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