Grating Design for 3-D Interconnections of Waveguides in Overlaid Chips Using the RCWA-EIS Method

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Abstract: The rigorous coupled-wave analysis – equivalent-index-slab (RCWA-EIS) method is used to determine the diffraction efficiencies of gratings for 3-D coupling between overlaid chips. The simulation results are validated by FDTD calculations.

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

1. Introduction

Optical interconnects offer promising solutions for large-scale integration. The development of multilayer platforms with interlayer optical connectors is crucial to provide rerouting schemes to avoid waveguide congestion and crossing on a single layer. Diffractive gratings are compact optical connectors and improving their coupling efficiencies has been an important topic in the fields of interconnects and packaging. However, most optimization work on grating couplers is time-consuming, e.g., using FDTD [1], COMSOL Multiphysics [2], or CAMFR [3] simulation packages, and less comprehensive, e.g., only providing a single design for a particular material system [4]. Therefore, we have introduced the RCWA-EIS method [5], a simplified but more flexible version of RCWA-leaky wave approach [6], which is generally accurate, computational efficient, easy to implement, and applicable to any 1-D grating structure. A large parameter space, including coupling angle, grating period, grating thickness, grating slant angle, etc., can be optimized without the need for an educated initial guess. Thus, it provides an easy tool for system designers to determine optimal grating structures.

2. Simulation model

Cover, grating, waveguide, and substrate comprise the grating structure considered here. Taking advantage of the light reciprocity, the model focuses on the in-coupling process to optimize the interlayer coupling efficiency. As shown in Fig. 1, the light in-coupled to the +1 order experiences the same diffraction efficiency as the guided wave out-diffracted to +1 order. Only the 0 and +1 orders are considered in the model. The field amplitudes and phases at all interfaces of a given grating structure are first determined by the RCWA, and then the grating layer is replaced by multiple equivalent slabs which retain the field amplitudes and phases at the cover-grating interface and the grating-waveguide interface, as shown in Fig. 2 (A binary grating is taken as an example.). Subsequently, the radiation factor (α) of the multilayer structure is calculated and the diffraction efficiency into the cover of the +1 order ($DE_{c,+1}$) is determined. The interlayer coupling efficiency, *CE*, is estimated as square root of $DE_{c,+1}$. The optimization of *CE*, or more directly, $DE_{c,+1}$, is carried out with the Matlab function *fmincon*. In order for in-coupled light to be guided in the waveguide, the x component of the propagation constant of the +1 order, $k_{x,+1}$, should be comparable to the fundamental propagating mode in the slab waveguide, β_0. Furthermore, diffraction orders other than 0 and +1 should be evanescent in all layers; that is, $k_{x,i} > k_0 n_w$, where i indicates i-th order ($i \neq 0$, +1) and n_w is the refractive index of waveguide. The details of the formulations and optimization were introduced in [5].

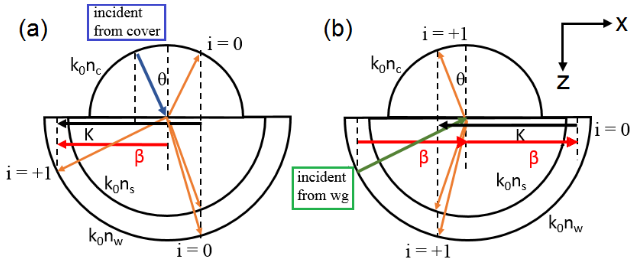

Figure 1: Wavevector diagram of (a) the grating in-coupling and (b) the out-diffraction process with only 0 and +1 orders. The light in-coupling to the +1 order (a) is the reciprocal process of the guided-wave out-diffracted to the +1 order (b).

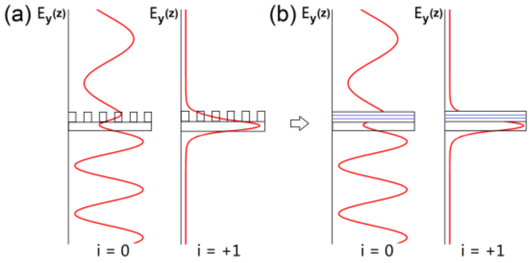

Figure 2: (a) Electric field inside and outside of the grating. (b) Electric field outside the grating when the grating is represented by equivalent slabs.

3. Simulation results

Four types of grating structures, namely binary gratings, parallelogramic gratings, sawtooth gratings, and volume gratings are analyzed to demonstrate the flexibility of the model. For the three types of surface-relief gratings, coupling angle θ, grating period Λ, and grating thickness t_g are the unknowns to be optimized. The other parameters are as follows: free-space wavelength $\lambda_0 = 1.55\ \mu m$, cover, waveguide, substrate, grating groove, grating ridge indices $n_c = 1$, $n_w = 3.45$, $n_s = 1.45$, $n_{gr} = 1$, $n_{rd} = 2.46$, fill factor $f = 0.5$, and waveguide thickness $t_w = 0.22\ \mu m$. The optimal slant angle of the parallelogramic grating can be calculated once the grating period is determined [7].

The volume grating considered here is a section of the waveguide instead of a structure deposited on top of the waveguide as in the cases of surface-relief gratings. The grating permittivity varies sinusoidally. Coupling angle θ, grating period Λ, and slant angle φ are unknowns to be optimized. The other parameters are as follows: $\lambda_0 = 1.55\ \mu m$, $n_c = 1$, $n_w = 1.8$, $n_s = 1.45$, $t_w = 0.4\ \mu m$, $t_g = 0.4\ \mu m$, average grating index $n_g = 1.8$, and index modulation $\Delta n_g = 0.1$.

The single grating diffraction efficiencies ($DE_{c,+1}$) as a function of number of grating periods (N) of selected optimized gratings are shown in Fig. 3. Corresponding optimized values are summarized in Table 1. The results obtained from the RCWA-EIS match well those calculated by the FDTD.

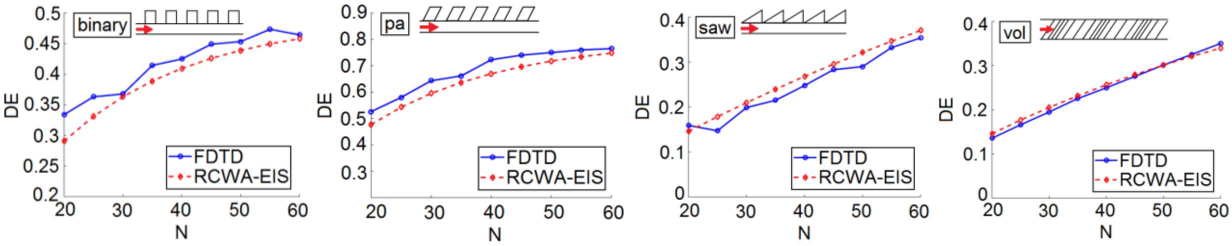

Figure 3: Single grating diffraction efficiencies (DEc,+1) as a function of number of grating periods (N) for selected cases of optimized binary gratings, parallelogramic gratings, sawtooth gratings, and the volume gratings.

Table 1: Optimized parameters and calculated coupling efficiencies for selected cases of binary gratings, parallelogramic gratings, sawtooth gratings, and the volume gratings. $PC_{c,+1}$ is the preferential coupling ratio, defined as the fraction of the total radiation power that is diffracted into the +1 order in the cover.

Case name	Initial values				Optimized values							
	θ rad	Λ μm	t_g μm	φ rad	θ rad	Λ μm	t_g μm	φ rad	$PC_{c,+1}$	$DE_{c,+1}$ @N=50	β μm^{-1}	α μm^{-1}
binary	0.30	0.60	0.10	---	0.3000	0.6000	0.2340	---	0.4914	0.4392	9.2742	0.0375
pa	0.10	0.55	0.30	---	0.2350	0.5500	0.3000	0.9831	0.8005	0.7177	10.4801	0.0412
saw	0.10	0.55	0.20	---	0.3732	0.5013	0.3413	---	0.8925	0.3214	11.0561	0.0089
vol	0.30	0.70	---	1.20	0.1041	0.7019	---	0.9255	0.5968	0.3010	6.7298	0.0098

4. Summary

The optimization of coupling efficiencies of arbitrary 1-D gratings is achieved using the RCWA-EIS method. The advantages of this optimization method are as follows: an arbitrary choice of grating profile, wide parameter search space, easy implementation, fast calculation, and accurate results. The RCWA-EIS method is generally robust for grating structures with large ($\alpha > 0.01\ \mu m^{-1}$) and small ($\alpha < 0.01\ \mu m^{-1}$) radiation factors, though small factors may require multiple initial guesses of α_0.

5. References

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