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Systematic design process for slanted grating couplers

Bin Wang, Jianhua Jiang, and Gregory P. Nordin

We have developed a systematic design process for recently proposed slanted grating couplers (SGCs) that operates in the strong coupling regime. Based on rigorous analysis of SGC properties, this design process utilizes the \mathbf{k} -vector diagram and a rigorous grating leaky-mode solver to intentionally enforce the phase-match and Bragg conditions. We demonstrate that the resultant SGC designs have performance similar to those obtained by parallel micro-genetic algorithm (μ GA) optimization with the two-dimensional finite-difference time-domain (2D FDTD) method. Only two 2D FDTD simulations are necessary in the later stages of our systematic design process. Therefore the time saving is tremendous compared to a μ GA 2D FDTD design tool, which can require thousands of individual 2D FDTD simulation runs. We illustrate the utility of our new systematic design process with an embedded slanted grating coupler example. © 2006 Optical Society of America

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Recently we proposed compact and efficient slanted grating couplers¹ (SLGCs) and embedded slanted grating couplers.^{2,3} (ESGCs). The difference between SLGCs and ESGCs is the location of the slanted coupling grating relative to the planar waveguide core. In SLGCs the coupling grating is on top of the core, while in ESGCs it is embedded in the core. These devices can be useful to vertically couple light from fibers into planar waveguides without intermediate optics.

Both SLGCs and ESGCs operate in the strong coupling regime in order to realize short coupling lengths that are of the order of a fiber mode diameter. Therefore their underlying physical coupling mechanism is different from traditional grating couplers that operate in the weak coupling regime in that leaky modes supported by the strongly modulated grating structure play an important role.⁴ In addition, the characteristics of these leaky modes are a function of all of the grating parameters such as grating fill factor, period, and slant angle.⁵ This makes analytic determination of the grating period from the phase-match condition impossible. The design and optimization of strong grating couplers is thus more complicated than weak grating couplers. However, there is little

work available in the literature on strong grating coupler design.

In previous papers,^{1–3} we employed a powerful parallel design tool based on micro-genetic algorithm optimization in conjunction with two-dimensional finite-difference time-domain analysis (μ GA 2D-FDTD), to rigorously design SLGCs and ESGCs. Although some efficient devices have been successfully obtained by this automatic design tool, this approach has two disadvantages. First, it does not inherently give us intuitive insight into the principles of strong grating couplers due to the built-in random process of μ GA and the purely numerical nature of the FDTD simulation. Second, the μ GA 2D-FDTD design process is time consuming. This is mainly due to the high computational load imposed by FDTD simulation with a Yee cell size small enough for reasonable accuracy. For instance, the uniform silicon-on-insulator embedded slanted grating coupler structure in Ref. 2 had a FDTD computational area of $30\ \mu\text{m} \times 1.5\ \mu\text{m}$ and a Yee cell size of $10\ \text{nm} \times 10\ \text{nm}$. This design takes about 14 days for 500 μ GA generations on a four-node cluster, each of which uses a PC with a 2.0-GHz CPU and 1.0 GBit of RAM.

In this paper, we propose a general and systematic design process for SLGCs and ESGCs. This design process is based on a thorough analysis and deep understanding of the basic physical characteristics of SLGCs and ESGCs as presented in Refs. 1–3. In this analytical design process, the grating fill factor and slant angle are first chosen according to fabrication constraints. Then a \mathbf{k} -vector diagram is utilized to determine the grating period so that phase-matching

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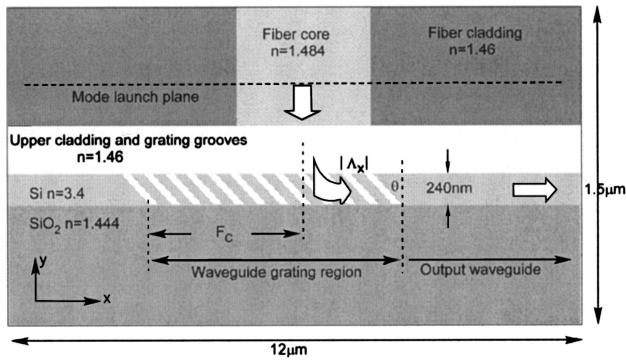


Fig. 1. Schematic diagram of ESGC geometry.²

and Bragg conditions are satisfied. A rigorous leaky-mode solver is employed to examine the existence of leaky modes at the designed slant angle. After the grating period, fill factor and slant angle are determined through the above process; a single-case 2D FDTD simulation is used to determine other parameters of the device, such as the fiber offset relative to the grating position. Since the large number of computationally intensive FDTD simulations is avoided in the proposed design process, it is significantly faster compared to the μ GA 2D-FDTD design approach. Device designs resulting from the new systematic design process have performance similar to those obtained by parallel μ GA 2D-FDTD. Moreover, if desired, the systematic design approach can be used to provide a good starting point for parallel μ GA 2D-FDTD for further optimization.

We first briefly review the physical analysis of SLGCs and ESGCs. The basic geometry and relevant physical parameters for an ESGC is shown in Fig. 1. The grating is embedded in the waveguide core region with an overlying upper cladding that fills the grating grooves. The single-mode planar waveguide has a 240-nm-thick core layer of Si with refractive index 3.400 and a lower cladding of SiO₂ with refractive index of 1.444. The upper cladding is assumed to have a refractive index of 1.460. The μ GA optimized grating parameters from Ref. 2 are the following: grating period (Λ_x) 0.6495 μ m, fill factor (f , the ratio of the low-index grating groove width to the period) 0.328, and slant angle (θ) 59.71°.

A \mathbf{k} -vector diagram can be constructed for this ESGC design from the diagram through rigorous leaky-mode analysis, as shown in Fig. 2. It is clear that the phase-match condition is realized for the fundamental leaky mode (effective index of 2.3864) in the grating region through the +1 diffraction order of the grating. Also notice that the Bragg diffraction condition is nearly satisfied in this case, which is a key factor to suppress other diffraction orders and to ensure efficient unidirectional coupling in the optimized ESGC. The \mathbf{k} -vector diagram and the rigorous leaky-mode solver play central roles in our proposed systemic design process.

When designing a uniform slanted grating coupler, the crucial grating parameters that first need to be

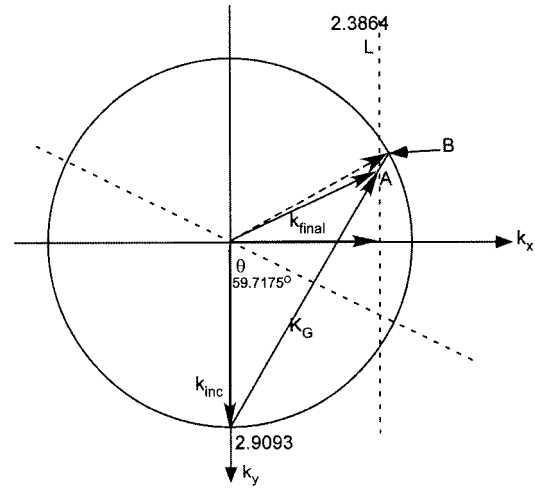


Fig. 2. \mathbf{k} -Vector diagram of the μ GA 2D FDTD optimized ESGC.²

determined are the grating period along the x direction (Λ_x), the grating slant angle (θ), and the fill factor (f). This is because the performance of strong grating couplers is very sensitive to these parameters. In addition, the number of grating periods and the relative position between the incident fiber and the grating also need to be optimized.

In the proposed systematic design process, we can determine these parameters by constructing the \mathbf{k} diagram according to the five steps discussed below. Figure 2 can be used to visualize the graphic elements discussed in these steps. Note that all \mathbf{k} vectors in the \mathbf{k} diagram are normalized by \mathbf{k}_0 , which is the wave vector in vacuum.

Step 1. Choose a grating fill factor by considering fabrication feasibility, for example, 0.5. As a zeroth-order approximation, the layer of the slanted grating can be treated as a homogeneous layer with an average refractive index, defined as the volume average between the two materials forming the grating. Once a fill factor is fixed, n_{ave} can be calculated as⁶

$$n_{ave} = \sqrt{n_1^2 \times \text{fillfactor} + n_2^2 \times (1 - \text{fillfactor})}. \quad (1)$$

We can now start constructing the \mathbf{k} diagram by drawing a circle of radius n_{ave} and the incident vector \mathbf{k}_{inc} .

Step 2. Select a slant angle for the grating and draw a slanted dotted line at this angle through the origin. Since the grating vector must be perpendicular to the slanted line, we can easily determine the grating vector direction. In addition, the Bragg condition must be satisfied in order to ensure high coupling efficiency. This means that the grating vector must terminate on the circle drawn in step 1. From a simple geometrical relation, the grating period Λ_x can thus be directly calculated as

$$\Lambda_x = \frac{\lambda_0}{\cos(2\theta - 90^\circ) \times n_{ave}}. \quad (2)$$

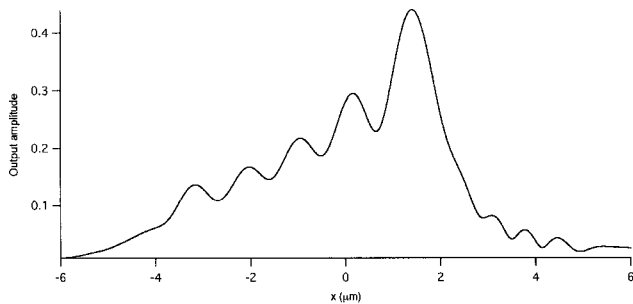


Fig. 3. Cross section of the near field of the output coupler calculated by 2D FDTD.

Assuming first-order operation of the grating, we can draw the grating vector. The \mathbf{k} diagram appears complete but may not be physical because the phase-matching condition is not yet enforced. This is accomplished by iterations as described below.

Step 3. Numerically determine the effective index, n_{eff} , of the fundamental leaky mode using a rigorous leaky-mode solver, such as the rigorous coupled-wave analysis mode solver we used in Refs. 1–3. Compare the value of L (x component of the final \mathbf{k} vector, as shown in Fig. 2) in step 2 and n_{eff} . Scan different slant angles by repeating steps 2 and 3 until a slant angle is found for which L matches n_{eff} . This means that both the phase-match and Bragg conditions are satisfied at the same time. The optimum slant angle and grating period can usually be determined within 20 iterations.

Step 4. Once the grating structure is fixed, a 2D FDTD simulation is performed on the final structure obtained from the above process as an output coupler to determine the fiber position relative to the grating, F_c (the distance between the center of the fiber and the left edge of the grating). This can be achieved by calculating the fiber position that maximizes the mode overlap integral between the fiber mode and the grating output field. Note, according to the reciprocity between input and output grating couplers,⁷ the output coupling efficiency should be the same as the input coupling efficiency.

Step 5. The final grating structure is modeled with 2D FDTD to evaluate its performance and to verify the design.

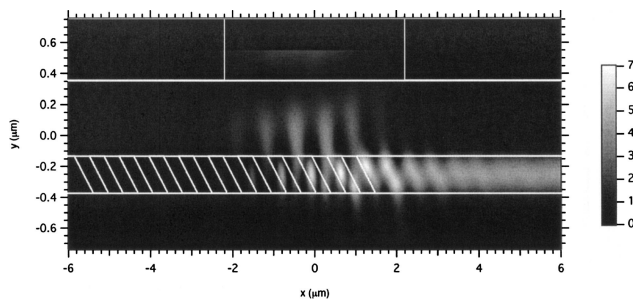


Fig. 4. 2D FDTD result of magnitude-squared time-averaged E_z component of input coupler with fill factor of 0.5.

The advantage of the above systematic design process is that only two FDTD simulations are needed. It is therefore much faster than μ GA 2D FDTD, which needs at least one thousand FDTD simulations. In addition, both the phase-matching and Bragg conditions are intentionally enforced during the design process. Consequently it is expected that the resultant SLGC and ESGC should have performance similar to structures directly optimized by our μ GA 2D FDTD design tool.

To demonstrate the proposed systematic design process, we present an ESGC design with an arbitrarily chosen fill factor of 0.5. By repeating steps 2 and 3 of the design process, the optimum slant angle to satisfy both the phase-match and Bragg conditions can be determined. It is found to be 62.5° , and the corresponding Λ_x is $0.723 \mu\text{m}$. 2D FDTD simulation of this grating as an output coupler reveals that 14 grating periods are sufficient because the field is near zero by this point. The output field above the grating, which is shown in Fig. 3, can be matched by a high-index fiber with a core size of $4.4 \mu\text{m}$ and core and cladding indices of 1.4840 and 1.4600, respectively. The maximum coupling efficiency occurs at $F_c = 5.39 \mu\text{m}$ with a 57.8% coupling efficiency. As the last step, 2D FDTD simulation of the whole structure as input coupler shows that the input coupling efficiency is 58.9%. The FDTD simulated result of the magnitude-squared time-averaged E_z component is shown in Fig. 4 for operation as an input coupler. As a comparison, we also use μ GA 2D FDTD to directly optimize the structure with a fixed fill factor 0.5. The optimized device has very similar physical parameters, and the input coupling efficiency is 62.1%. Thus, our new design procedure yields a result with an optical efficiency that is only slightly smaller than μ GA results.

In summary, we have developed a systematic design procedure for slanted grating couplers based on a physical understanding of slanted grating coupler operation in the strong coupling regime. Since a large number of FDTD simulations are not involved in this design process, it is less time consuming compared to using our μ GA 2D FDTD design tool. The resultant devices generally have similar performance to those optimized by μ GA 2D FDTD.

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