Analysis and Design of Grating Couplers

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Abstract. Based on an accurate perturbation analysis of the guiding properties of dielectric gratings, simple design criteria are developed for grating couplers which transfer the energy of a beam into or out of an optical waveguide. Gratings having arbitrary groove shapes are considered and explicit formulae are given for the leakage parameters of gratings with symmetric profiles. The results cover TE_0 and TM_0 modes and they apply to both shallow and deep grating grooves. The variation of the leakage parameter \varepsilon in rectangular gratings is examined in detail; these rectangular gratings are then used as basic configurations for predicting the characteristics of other grating profiles. Particular attention is given to trapezoidal and triangular profiles and gratings with asymmetric profiles are also discussed.

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Dielectric gratings have found increasing applications as couplers of light beams into thin-film optical waveguides. Because of their growing importance, theoretical studies of such grating couplers have been quite numerous and they have included both exact and approximate formulations [1]. However, rigorous treatments [2, 3] of the pertinent boundary-value problem are quite complex and require time-consuming and elaborate high-precision computer programs to yield accurate quantitative results. To avoid this, perturbation procedures have been proposed [1, 4–10] for obtaining approximate results, but most of these are restricted either to grating having shallow grooves or to specialized applications. The results so far available have therefore not been adequate to develop systematic criteria for the design of grating couplers.

The purpose of the present work is to review general qualitative guidelines and to present reliable quantitative expressions for both the analysis and the design of grating couplers. Our analysis is based on an improved perturbation approach, which was shown to be suitable for application to a large variety of beam coupling configurations [11–15]. In contrast to other methods, this approach is not restricted to shallow grating grooves and it can be applied to arbitrary grating profiles. Also, our analytic formulation of the electromagnetic fields can be viewed in terms of equivalent transmission-line networks that lend considerable insight into the wave-coupling mechanism. These networks enable one to assess the role of each grating parameter and to predict the change in coupling performance as any one of the parameters varies; they are therefore particularly useful for design considerations.

The mathematical derivation of the improved perturbation results for the electromagnetic coupling problem is given in an Appendix, which essentially consolidates and simplifies all of the work of [11–15]. An important feature of this simplification is that it leads to approximate but explicit formulae that express the principal coupling effects directly in terms of the known grating parameters.

We review the grating-coupler operation and its design problem in Sect. 1 and show that the power leakage away from the grating is the factor that plays the single most important role in the beam coupling process. We therefore discuss in Sect. 2 the variation of leakage as a function of the grating parameters, and explicit for-
1. Basic Design Requirements

A unified interpretation of beam couplers of the prism and grating varieties is to regard both devices as surface-wave-to-leaky-wave converters [1]. For grating couplers, this is illustrated in Fig. 1 where the upper sketch describes an output coupler, which converts a surface wave into outgoing beams, whereas the lower sketch describes an input coupler, which converts an incoming beam into a surface wave.

In usual practice, the field distribution can be taken invariant with \( y \), so that the two-dimensional condition \( \partial \psi / \partial y = 0 \) will be assumed herein. In the output coupler of Fig. 1a, a surface wave varying as \( \exp [i(\beta_{sw}x - \omega t)] \) is incident onto the grating from the left. The grating scatters the incoming energy into space-harmonic fields that vary as \( \exp [i(k_{x,n}x - \omega t)] \) where \( k_{x,n} \) is related to the grating period \( d \) by

\[
k_{x,n} = \beta_n + ik = \beta_0 + (2n\pi/d) + ik, \quad (n=0, \pm 1, \pm 2 \ldots) .
\]

Unless the grating layer has a permittivity \( \varepsilon_g \) which is substantially larger than the permittivity \( \varepsilon_f \) of the film waveguide, the fundamental term \( \beta_0 \) is closely equal to the propagation factor \( \beta_{sw} \) of the incident surface wave. In addition, the decay factor \( \alpha \) is usually very small, so that we may assume

\[
\beta_0 \approx \beta_{sw} > k_o = 2\pi/\lambda \quad \text{and} \quad \alpha \lambda < 1 ,
\]

where \( \lambda \) is the wavelength in air.

The factor \( \alpha \) is due to the leakage of the energy into the diffracted orders scattered by the grating. Because of this leakage, each scattered field is in the form of a leaky-wave beam. Hence the grating coupler shown in Fig. 1a is regarded as a structure that transforms a surface wave into one or more leaky waves. These waves radiate into the air region at angles

\[
\phi_n = \sin^{-1}(\beta_n/k_o), \quad (n=0, \pm 1, \pm 2 \ldots).
\]

Thus, radiation away from the grating occurs only for those waves that satisfy \( |\beta_n/k_o| < 1 \) since otherwise \( \phi_n \) cannot be real. Because (2) indicates that \( \beta_0 > k_o \), radiation can occur only for \( n < 0 \).

The number of outgoing beams can therefore be minimized by selecting a value of \( d \) so that \( |\beta_n/k_o| < 1 \) is satisfied for only a few values of \( n < 0 \). To obtain a single beam in the upper air region, we require \( |\beta_{-1}| < k_o \) and \( |\beta_{-2}| > k_o \); the latter condition implies that \( |\beta_{-1}| > k_o \) for all \( n < -1 \). In the substrate we must then have a corresponding outgoing beam, which is refracted into the lower air region. However, unless we satisfy the more stringent condition \( |\beta_{-2}| > k_o \sqrt{\varepsilon_s} \), where \( \varepsilon_s > 1 \) is

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Fig. 1a and b. Grating couplers viewed as surface-wave to leaky-wave converters: (a) Output coupler; (b) Input coupler. A single diffraction order (for \( n = -1 \)) is assumed to propagate. Dimensions are not drawn to scale.