MICROWAVE MODELS OF BLAZED DIELECTRIC GRATINGS FOR INTEGRATED-OPTICS APPLICATIONS

T. Tamir
Department of Electrical Engineering
Polytechnic Institute of New York
Brooklyn, NY 11201

Abstract

The behavior of leaky modes along microwave gratings shows that: (1) a Bragg-scattering approach provides simple design criteria for blazed dielectric gratings, and (2) broadband, highly efficient, optical beam-coupling devices using such gratings can be easily realized.

Summary

Dielectric gratings have been extensively used in integrated optics[1] to convert an incident light beam into a guided surface wave, or vice-versa. Because gratings having symmetric profiles can generally couple energy equally well into both the regions above and below the grating, the maximum coupling efficiency is usually about 50%. On the other hand, gratings with "blazed" asymmetrical profiles may theoretically[2-7] yield nearly 100% efficiency because they can selectively scatter the energy of a surface wave into only one of the two regions. At optical wavelengths, the experimental verification of such a scattering performance has been limited[8] and the sensitivity of this blazing effect with frequency or with the grating parameters cannot easily be assessed. We therefore report here the realization of microwave models for blazed dielectric gratings that strongly discriminate between the upper and lower regions over a wide range of grating parameters and wavelengths. In particular, we have obtained coupling efficiencies higher than 94% near the band center.

As shown in Fig. 1, the basic geometry of a dielectric optical grating involves a periodic layer superimposed on a thin-film waveguide of thickness t_f backed by a substrate, with n_u(u = a, r, f and s) denoting the refractive index of the upper (air), grating, film and substrate regions, respectively. For an incident surface wave propagating as $\exp(i\beta x)$, Chang and Tamir have developed a Bragg-scattering approach[6] which asserts that energy leakage is maximized into the upper (air) region if $\gamma_2 = 0$ and $\gamma_2 = \gamma_B$, where γ_B satisfies a Bragg-type condition[7]

$$\tan \gamma_B = \frac{d}{t_g} = \left[\frac{n_g + N - (\lambda/d)}{n_g - N + (\lambda/d)}\right]^{\frac{1}{2}} \qquad (1)$$

Here λ is the wavelength in vacuum, $N = \beta\lambda/2\pi$ is the effective refractive index of the optical guide and $n_g = \epsilon_g^{\frac{1}{2}}$, where ϵ_g is the average dielectric constant inside the periodic region ($0 < z < t_g$). Because the parameters n_g, N, λ and d are usually given, relation (1) together with $\gamma_2 = 0$ serve as simple criteria for designing dielectric gratings with strong blazing properties. Furthermore, these properties are predicted[7] to hold over a frequency range given by

$$\frac{\Delta f}{f} = \pm \frac{n_r^2 - n_a^2}{4n_g^2 \cos^2 \gamma_B}, \qquad (2)$$

where Δf is the maximum frequency increment that is consistent with good blazing performance, i.e., $\eta_a \simeq 90\%$ or larger. For operation at microwave frequencies, the grating structure can be made of teflon having air for both the upper and lower regions, so that $n_r = n_f = 1.414$ and $n_a = n_s = 1.0$. Because its fundamental TE_0 mode has electric field components in the y direction only, the grating can be placed between metallic conductors without affecting that field, which is then designated as the TE_{00} mode. We have consequently used an aluminum parallel-plate arrangement as shown in Fig. 2, where the x, y and z directions correspond to those of Fig. 1. The separation between the plates was taken equal to the height b = 0.4" of an X-band (8-12 GHz) rectangular waveguide, which fed energy to the grating via a flange coupler.

Because the TE_{10} mode of the rectangular guide is well matched to the TE_{00} mode in the parallel-plate system, the incoming wave is smoothly coupled to the (leaky) surface wave supported by the teflon grating. To further improve this match, the input end of the grating structure was suitably tapered into the rectangular waveguide. As the TE_{00}-mode surface wave travels down the grating, it leaks power obliquely to the grating and in a direction parallel to the xz plane; the field therefore varies longitudinally as $\exp(i\beta x-\alpha x)$. By probing this scattered power along x with movable detectors, we have determined: (a) the ratio between the field amplitudes on the two sides of the grating, and (b) the decay α of these amplitudes along x.

Illustrative results for $\alpha\lambda$ and η_a are given in Fig. 3 for a grating that satisfies condition (1) at a design-center frequency f = 10 GHz. Here η_a represents the percentage of power radiated into the air region adjacent to the periodic portion of the grating. Thus η_a = 100% implies that all of the surface-wave power is beamed into the right-hand side region of the parallel plate in Fig. 2, i.e., into the upper (air) region in Figs. 1 and 3. As seen in Fig. 3, a peak of η_a = 98.4% was actually measured close to the center frequency. Theoretical data are shown for both η_a and $\alpha\lambda$ by solid lines, which were calculated by a very accurate numerical solution of the exact boundary-value problem.[9] The measured results are very close to the theoretical results, which predict a peak value of η_a = 99.5% at f = 10.3 GHz. In addition, Eq. (2) implies that $\eta_a > 90\%$ for $7.8 < f < 12.2$ GHz and this range is confirmed well in Fig. 3.

By using several such microwave models of optical gratings and by changing some of the grating parameters, we have demonstrated the feasibility of blazed dielectric gratings showing strong scattering discrimination between the two sides of their periodic configuration. We have also found that this selectivity is not affected by practical fabrication tolerances and that it holds over a broad frequency band. As all of these results are fully consistent with the Bragg-scattering approach to the grating operation, the design criteria derived by that approach can be used to develop high efficiency beam-coupling devices for integrated optics, which can operate over wide frequency bands and which are not subject to stringent fabrication tolerances.

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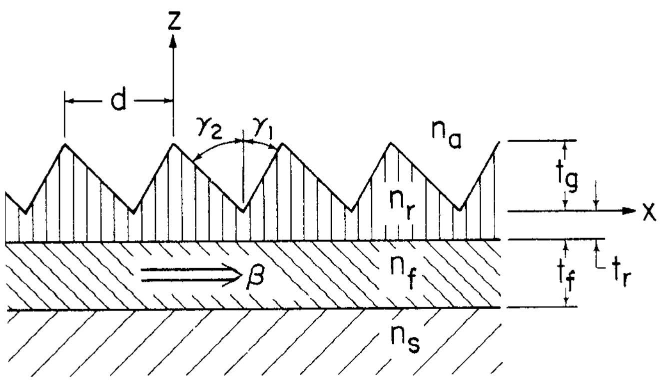

Fig. 1. Geometry of the dielectric grating.

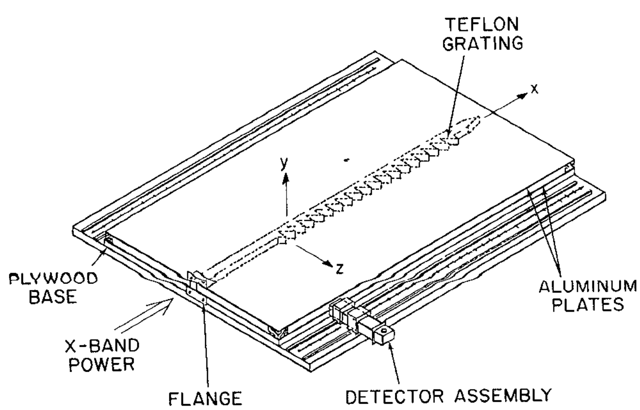

Fig. 2. X-band microwave set-up for measuring models of optical gratings.

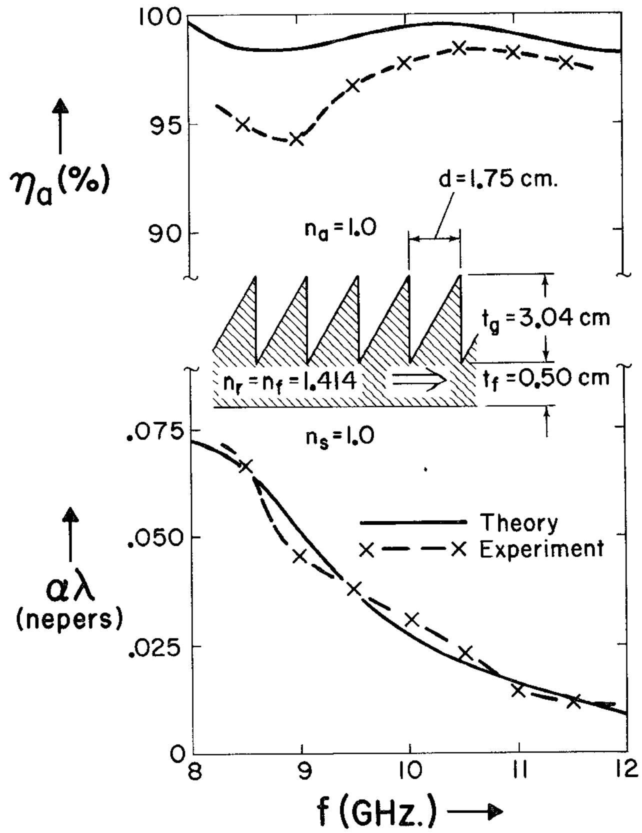

Fig. 3. Variation of efficiency η_a and leakage $\alpha\lambda$ vs frequency f for a blazed grating that satisfies condition (1) at λ = 3.0 cm., in which case N = 1.097 for the TE_0 mode.