NETWORK METHODS FOR DIELECTRIC-GRATING APPLICATIONS

T. Tamir and S. T. Peng
Department of Electrical Engineering and Electrophysics
Polytechnic Institute of New York, Brooklyn, N.Y. 11201

Abstract

The application of network methods to the analysis and design of integrated-optics components is illustrated for the case of dielectric gratings, which are relevant to optical beam couplers, filters and distributed-feedback lasers. The advantage of the network representation in those cases is that the role of each grating parameter can be interpreted in terms of the network elements. In addition to yielding physical insight into the electromagnetic field behavior, the network approach greatly facilitates the design and construction of dielectric gratings having efficient operation or other desired characteristics.

The similarities between guided-wave components in the two areas of integrated optics and microwave engineering have been well recognized. However, while equivalent networks involving lumped and distributed elements have served as a powerful tool in treating a wide range of microwave problems, the use of network methods in integrated optics has been so far very limited in scope. The aim of this paper is to show the effectiveness of equivalent networks in integrated optics by presenting their novel application to dielectric gratings, which play a dominant role in beam couplers, filters, distributed-feedback lasers and other devices that incorporate periodic structures.

Network terminology has already been employed in the early microphotolithographic work at infra-red,[1] while equivalent networks have been subsequently used mostly in transverse-resonance analysis of dispersion curves for thin-film waveguides of the strip[2] or planar varieties.[3] Most recently, dielectric gratings of the type sketched in Fig. 1 have been shown[4] to be rigorously described by the transverse network configuration given in Fig. 2. Here B denotes a lossless network that couples all of the space harmonics, each of which is represented by a transmission-line circuit in the regions outside the grating. Whereas the complete network is rather complicated if a large number of space harmonics must be accounted for, it nevertheless leads to systematic computational procedures for structures with a larger number of layers and/or for gratings having more complex profiles.

A great simplification in the equivalent network of Fig. 2 can be achieved by adopting a perturbation approach[5] which assumes that the grating region appears as a modification of a uniform layer having a relative permittivity ϵ_g. One can then express the permittivity in that layer as

$$\epsilon(x) = \epsilon_g[1+ \sum_{n\neq 0} \epsilon_n \exp(i\frac{2n\pi}{d} x)], \qquad (1)$$

where the summation is regarded as a perturbation term. The electric field $E = E_y$ for TE modes can be written as

$$E(x,z) = \sum_n V_n(z) \exp(i\kappa_n x), \qquad (2)$$

where

$$\kappa_n = \kappa_0 + \frac{2n\pi}{d} \quad , \quad n = 0, \pm 1, \pm 2 \ldots), \qquad (3)$$

and κ_0 is generally complex.

If (1) and (2) are introduced into the wave equation and only first-order terms are retained, one gets

$$\frac{d^2 V_n(z)}{dz} + (k^2-\kappa_n^2)\, V_n(z) = - k^2\epsilon_n V_0(z), \qquad (4)$$

which holds for all $n\neq 0$. However, $V_0(z)$ represents a presumably known (unperturbed) incident field. Equation (4) implies that each partial electric-field (space harmonics) $E_n(x,z)$ in (6) can be found in terms

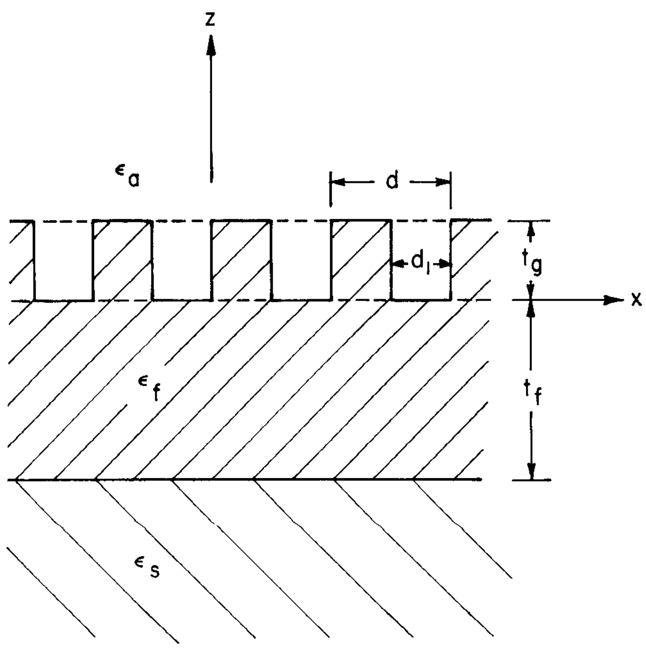

Fig. 1. Typical dielectric grating used in applications for integrated optics.

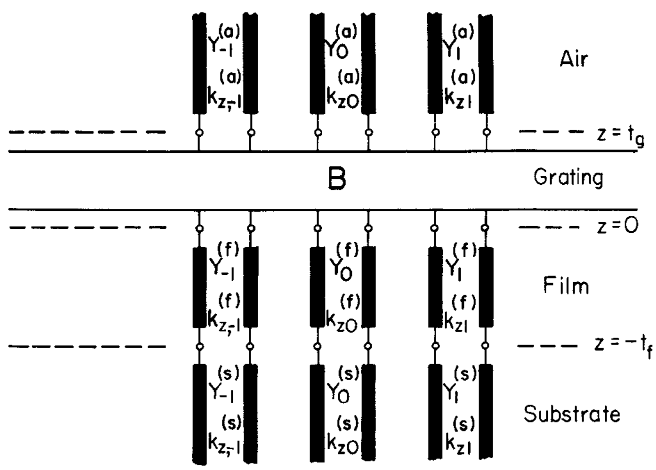

Fig. 2. Equivalent network representation of the dielectric-grating configuration

of the voltage $V_n(z)$ along the equivalent transverse network shown in Fig. 3. Unlike Fig. 2, the network in Fig. 3 is a simple, uncoupled and independent transmission-line circuit characterized by propagation factors $k_{zn}^{(u)}$ and characteristic admittances $Y_n^{(u)} = k_{zn}^{(u)}/\omega\mu_o$, where

$$k_{zn}^{(u)} = (k^2 \epsilon_u - \kappa_n^{\,2})^{\frac{1}{2}}. \quad (5)$$

Here the index u = a,g,f or s denotes the air, grating, film or substrate region, respectively. The voltage $V_n(z)$ is determined by the distributed current $j_n(z)$, which is proportional to the right-hand size of (4) and is known for any given incident voltage $V_0(z)$. A similar treatment holds for TM-modes, except that the voltage $V_n(z)$ is then determined by both distributed currents $j_n(z)$ and voltages $v_n(z)$ inside the grating region ($0 < z < t_g$), as indicated in Fig. 3.

The principal advantage of this simplified approach is that it can be easily applied to any given excitation problem. Thus, the incident field may be a plane wave impinging obliquely on the grating (for scattering phenomena), a surface wave traveling longitudinally (for beam-coupling or filtering applications), or a standing wave along the grating (for distributed-feedback lasers). Each one of these situations is distinguished from the other only by the fact that the voltage and current sources are different. However, these sources are known in every case, and they are simply prescribed by the given incident field. Because of their relative simplicity, equivalent networks such as that in Fig. 3 are extremely helpful in providing both physical insight and accurate quantitative evaluations for practical design problems.

As an example of an optical beam-coupler application, which requires a leaky-wave regime, Fig. 4 shows the normalized attenuation $\alpha d/2\pi$ of leaky waves supported by a corrugated GaAs wafer used in converting a light beam into a surface wave, or vice-versa. In this case, the minima and maxima of the curves can be directly related to the height t_g of the grating. As t_g varies, the transmission line between z = 0 and $z = t_g$ in Fig. 3 also varies; hence the leaked energy (and therefore α) exhibits maxima and minima because of the cyclic variations of the input impedances "seen" by the sources.

Another important advantage of this network approach is that it can handle gratings with arbitrary periodic profiles. Consequently, results can be obtained for configurations that, unlike the rectangularly corrugated grating of Fig. 1, do not lend themselves to an exact solution of the pertinent boundary-value problem.

A particularly interesting case is the asymmetrical triangular profile shown in Fig. 5(a), which can produce directional discrimination ("blazing") of incident surface wave. This is achieved by designing the grating so as to induce a stronger energy leakage into either the upper (air) or the lower (substrate) regions, depending on whether incidence is from the right or left, respectively, as suggested in Fig. 5(b). In network terms, the desired blazing effect is obtained by choosing the sources $j_n(z)$ and $v_n(z)$ so as to direct the power flow selectively into either the air or the substrate region. For example, the sources can be

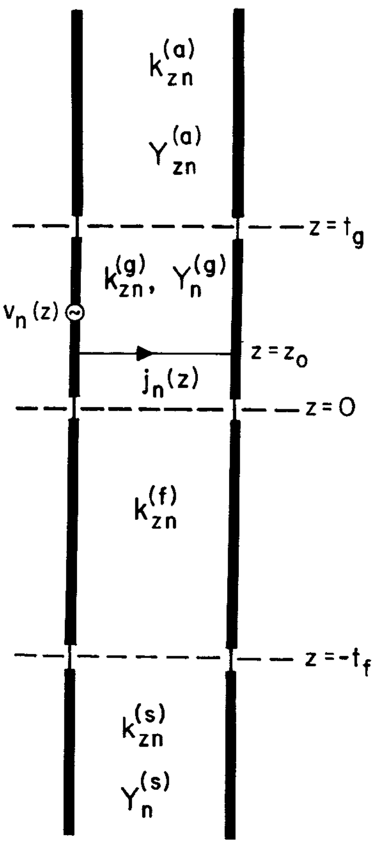

Fig. 3 Simplified network representation for TM-mode problems. For TE modes, the network is unchanged, but $v_n(z) = 0$.

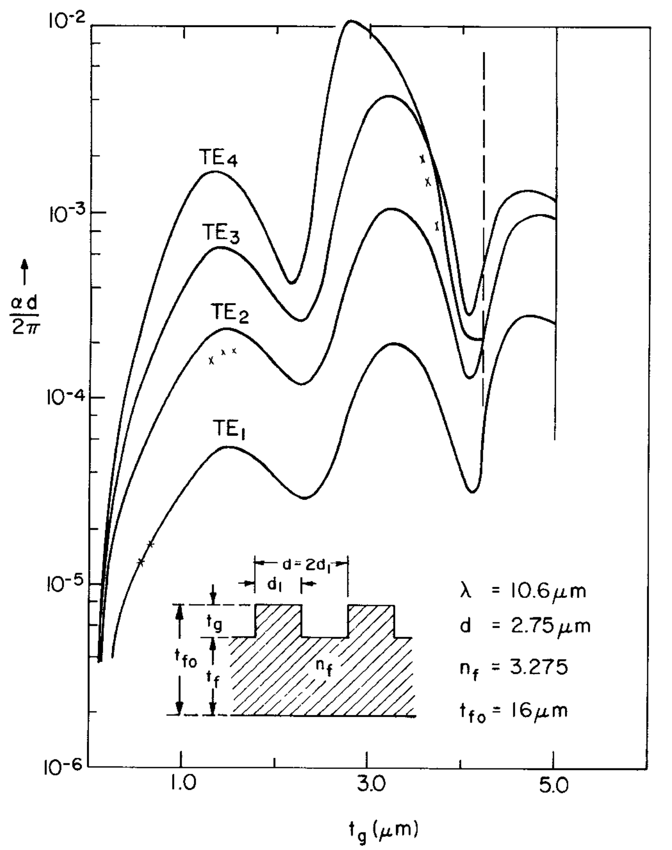

Fig. 4 : Normalized leakage $\alpha d/2\pi$ versus grating thickness t_g for several modes guided by a corrugated GaAs slab. Points X indicate results obtained by the exact analysis.

judiciously distributed along the transmission line segment $0 < z < t_g$ so as to interfere destructively for the field in the substrate region while interfering constructively for the field in the air region. After determining a suitable source distribution, the geometrical shape of the grating profile can be obtained by means of Fourier transforms.

To summarize, the greatest advantage of the equivalent-network representation is that it permits a direct interpretation of the grating characteristics in terms of the constituent parts of the transmission-line circuit. Thus, the leakage properties of grating couplers, the asymmetric behavior of triangular gratings, the Bragg-reflection regime of distributed-feedback lasers, etc. can all be phrased in terms of the transmission-line parameters and the fields associated with them. By extension, the application of such network methods to a wider class of integrated-optics configurations is expected to provide a powerful analytic technique for design-oriented purposes.

Acknowledgment

This work was supported by the Office of Naval Research under Contract No. N00014-75-C-0421, by the National Science Foundation under Grant No. ENG74-23908, and by the Joint Services Electronics Program under Contract No. F44620-69-C-0047.

References

1. D. B. Anderson, "Applications of Microphotolithography to Millimeter and Infrared Devices", Proc. IEEE, vol. 54, pp. 657-661; April 1966.

2. E. A. J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics", Bell System Tech. J., vol. 48, pp. 2071-2102; September 1969.

3. T. Tamir, "Inhomogeneous Wave Types at Planar Interfaces: II - Surface Waves", Optik, vol. 37, pp. 204-228; February 1973.

4. S. T. Peng, T. Tamir and H. L. Bertoni, "Theory of Periodic Dielectric Waveguides", IEEE Trans. Microwave Theory Tech., vol. MTT-23, pp. 123-133; January 1975.

5. S. T. Peng and T. Tamir, "TM-Mode Perturbation Analysis of Dielectric Gratings", Appl. Physics, vol. 6, pp. 35-38; May 1975.

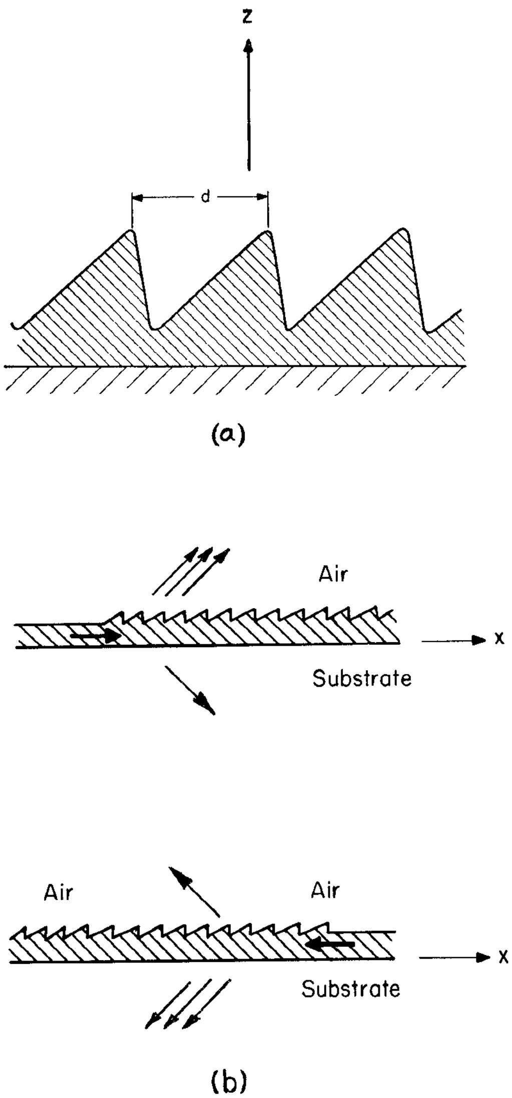

Fig. 5 : Blazing of surface waves:
(a) Asymmetric grating profile for directional discrimination of incident surface waves;
(b) Result of grating asymmetry, showing that a surface wave incident from the right is leaked mostly into substrate whereas a surface wave incident from the left is leaked mostly into the air region.