Leaky-Waves of Metal-Strip Gratings on Optical Planar Dielectric Slabs

Kwang-Chun Ho, June-Hwan Kim**, Yung-Kwon Kim***

*: Halla Institute of Technology, **: Kon-Kuk University

San 66, Heungup, Wonju, KangwonDo

kwangho@hit.halla.ac.kr

Abstract

The electromagnetic properties of leaky-waves guided by metal-strip grating configurations can be phrased in rigorous modal theory. Such a modal solution expressed by simple electrical transmission-line networks is utilized to analyze the leakage and filtering characteristics of metal-strip gratings. In particular, the modal transmission-line theory can serve as a template for computational algorithms that systematically evaluate the radiation effects that are not readily obtained by other methods.

I. Introduction

Optical periodic guiding structures made up of multilayered dielectric materials have been investigated for practical applications of such integrated optics as Bragg-reflection filters, distributed-feedback lasers and grating couplers [1]. Analogous structures based on periodic dielectric guides can be successfully used in the microwave and millimeter-wave range. In most cases, they can be easily fabricated by printing metal-strip gratings on the surface of dielectric slabs.

One of the most important applications of such periodic guides is to transfer the electromagnetic energy of a propagating mode to that of a directional radiation. Leaky-wave antennas of these types have some considerable merits like simplicity of fabrication, low cost, planar design and others [2-4]. The electromagnetic problems associated with the operation of leakage have been studied by means of a variety of methods that usually include a mixture of analytical and computer-based techniques [5, 6]. However, highly accurate but essentially numerical techniques are often unable to provide information on all the effects produced by the metal-strip gratings. As an example, one fails to determine the reliably accurate information on radiation leakage without considering the finite-thickness of metal-strip gratings.

To achieve the objective, in this paper we present some results for a dominant TE mode based on the rigorous transmission-line modal formalism. Note that although the obtained results refer to leakage and filtering characteristics of metal-strip gratings, this method is applicable to the most of multilayered grating configurations encountered in optoelectronic devices.

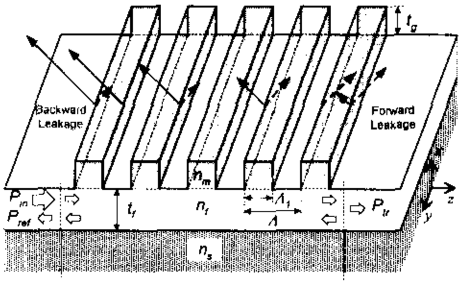


Fig. 1. Schematic configuration of metal-strip gratings printed on planar dielectric slabs.

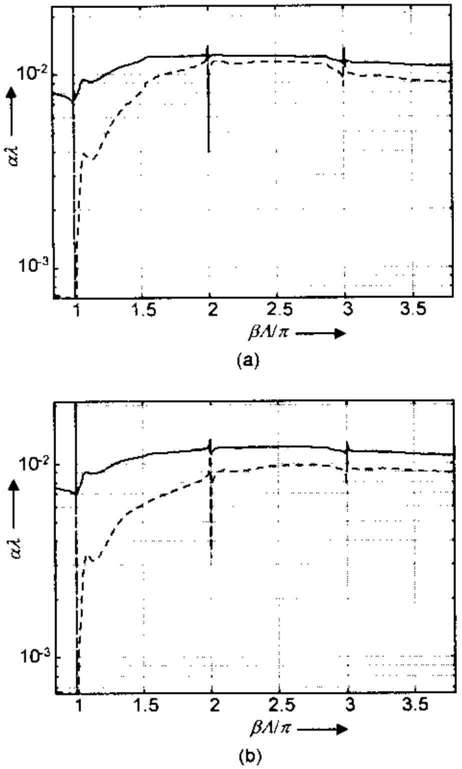
II. Modal Characteristics of Leaky-Waves

The geometry of the analyzed structure at operating wavelength λ=1.55 μm is shown in Fig. 1. Infinite number of metal-strips with the thickness t_g and the refractive index n_m, separated by the grating period Λ, is printed on the surface of a dielectric thin-film of the thickness t_f = 0.58 μm and the refractive index n_f=3.39. For this composite structure with a substrate of refractive index n_s=3.17, the complex propagation constant $k_{zn}=k_{zo}+2n\pi/\Lambda$ (in which the basic longitudinal propagation constant is $k_{zo}=\beta+i\alpha$ and n represents the space harmonics) can be calculated by applying the transverse resonance condition of modal transmission-line theory [7]

$$| \mathbf{Y}_{up} + \mathbf{Y}_{dn} | = 0 \quad , \qquad (1)$$

where $\mathbf{Y}_{up}$ and $\mathbf{Y}_{dn}$ indicate the admittance square matrices looking up and down at an arbitrary j-th layer boundary on x-axis, respectively. The unknown eigenvalue k_{zn} is then related to all the functional quantities included in Eq. (1), and is obtained from the eigenvalue problem given in Eq. (1) for the leaky-waves of metal-strip gratings.

Perhaps the most important properties of planar gratings are those associated with dispersion curves, which characterize the leaky-wave effects of the guiding structure. The basic curves for phase variation β are not appreciably different even if a grating thickness is finite, but those for leakage factor α usually exhibit higher values if that grating is leaky. However, very pronounced differences occur if the metal-strip grating is operated under a Bragg regime defined by $\beta\Lambda/\pi \approx$ q=integer. Under those conditions, $\alpha\lambda$ can become exceedingly large over a (usually narrow) frequency range that acts as a true stop-band or leaky-wave stop-band due to Wood anomalies [8].



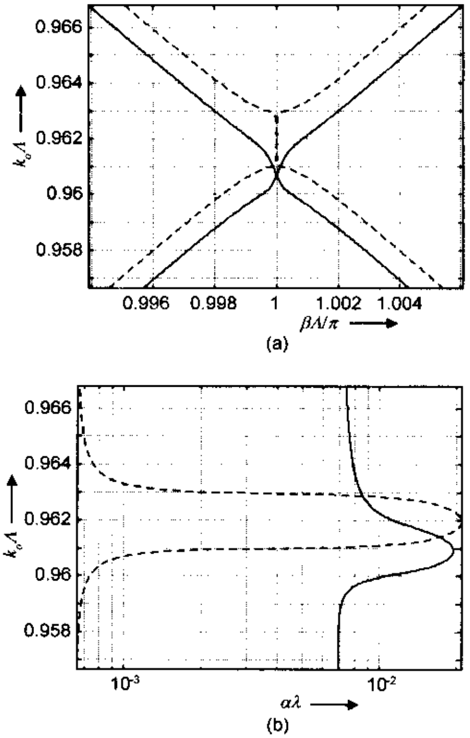
(a)

(b)

Fig. 2. Dispersion curves for the attenuation $\alpha\lambda$ as a function of Bragg-order $\beta\Lambda/\pi$: (a) t_g=0.05 μm, (b) t_g=0.15 μm.

Such a behavior is illustrated by the dispersion curves in Fig. 2, for which the gratings are comprised by *Au* or *Al* metal-srtips with refractive indices n_m =0.18+i10.2 or 1.04+i5.56, respectively. Figure 2 shows that the normalized leakage factor $\alpha\lambda$ can reach very large values at the Bragg points $\beta\Lambda/\pi \approx$ *integer numbers*, and the leakage effect decreases as increasing the thickness of metal-strip gratings from t_g=0.05 μm to 0.15 μm.

To clarify the impact of the narrow peaks in Fig. 2, we depict in details the variation of $k_o\Lambda$ with respect to both $\beta\Lambda/\pi$ and $\alpha\lambda$ in Fig. 3. Specifically, Fig. 3 displays the situation near the first-order (q=1) Bragg



(a)

(b)

Fig. 3. Details of the dispersion curves for t_g=0.15 μm at the first-order Bragg condition, where $k_o\Lambda$ is shown as a function of (a) $\beta\Lambda/\pi$ and (b) $\alpha\lambda$.

regime for which condition in integrated optics applications was intentionally chosen so that all spectral orders are evanescent, *i.e.*, no radiation space harmonics then exist. However, this appropriate condition is valid only for Au metal-strip gratings (dashed-lines) and not for Al gratings (solid-lines). As shown at the dashed-lines of Fig. 3(a), the frequency range over which no propagation occurs can be viewed as a gap that corresponds to a surface-wave stop band. The gap then acts as a true stop band in the sense that the forward- and backward-traveling waves are equal to each other inside that band while $\alpha\lambda$ varies between zero to a large maximum value and back to zero as depicted in Fig. 3(b). In contrast, the solid-lines show the situation around the Bragg regime under condition such that a radiating space harmonic is present because $\beta\Lambda=\pi$ is not constant. Hence the gap now corresponds to a leaky-wave stop band, which behaves only as a close approximation of a true stop band.

Although we do not address the detailed situations at the higher-order Bragg conditions, we can see also from Fig. 1 that the Bragg peaks for the dominant TE mode are suppressed at those conditions because a degenerate diffraction due to the metal-strip gratings of very high lossy dielectric constant occurs. These stop-band considerations acquired are familiar with results in the area of leaky-wave antennas at microwave and millimeter-wave frequencies. However, few of these aspects are explored in the optical range of guiding structure printed by metal-strip gratings.

Additionally, we note that the results obtained here for the duty cycle Λ_1/Λ emphasize that exact solutions may often be required. Based on approximate methods, it has so far been assumed that $\alpha\lambda$ varies with the duty cycle in a bell-shaped (cosine) form, with a peak at Λ_1/Λ=0.5. As seen from Fig. 4, the peaks occur at

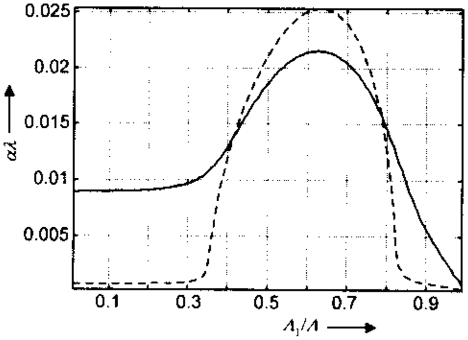


Fig. 4. Variation of $\alpha\lambda$ as a function of the duty cycle Λ_1/Λ, where the periodicity is $\Lambda\approx0.237$ μm and the thickness of metal gratings is t_g=0.15 μm.

values of A_1/A that are appreciably different from 0.5, and the curves varies along with arbitrary forms that may be dependent on the material properties of metal-strip gratings printed. Such variations of $\alpha\lambda$ with respect to A_1/A are rather unexpected and could be ascertained only by an exact analysis of the type presented here.

III. Conclusions

We have presented an efficient and rigorous approach to the analysis of leakage characteristics of narrow metal-strip gratings printed on the surface of planar dielectric slabs. The analytic evaluations are based on the modal transmission-line theory, which has been developed to study the grating configurations encountered in optoelectronic devices. The advantage of this approach is that it can be successfully applied to the metal-strip gratings of finite-thickness while the other approaches are not.

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