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Simple apodization technique for surface-corrugated waveguide gratings

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ABSTRACT

This paper reports a simple technique for suppressing the sidelobes outside the stop band of surface-corrugated waveguide gratings. To ensure the sidelobe suppression, the dc coupling coefficient arising from the dc component of the dielectric perturbation should be as small as possible. In the proposed waveguide grating, the periodic corrugation whose depth is reduced toward the ends of the grating is formed on both sides across the film-cladding boundary of the waveguide. The 2D simulation based on the coupled-mode theory has shown that the sidelobes can be substantially suppressed while maintaining the reflection within the stop band of the uniform grating. The proposed apodization technique is suitable for the sidewall corrugation from the viewpoint of the ease of fabrication.

1. Introduction

Surface-corrugated waveguide gratings (CWGs) are suitable for integrated optics devices and have a wide range of applications such as filters, laser source tuners, dispersion compensators, and grating couplers since the 1970's [1]. For example, in the grating devices required for wavelength-division-multiplexing (WDM) applications, the level of the sidelobes outside the stop band must be sufficiently reduced to avoid crosstalk between the adjacent channels. Such waveguide gratings are generally designed to satisfy desired characteristics by changing the amplitude or/and phase of the periodic modulations of refractive index or physical structure. The apodization can be made by gradually reducing the coupling coefficients, i.e., the dielectric perturbation induced by the waveguide deformation to zero at the ends of the grating. In CWGs reported to date, the periodic corrugation has been formed on the top (or bottom) surface or sidewalls of the waveguide and its depth [2–5] and duty cycle [6] have been adjusted to change the coupling coefficients. Although the device simulation has been performed by the coupled-mode theory (CMT) [7], it seems that the term of the dc coupling coefficient is often missing. The dc component of the dielectric perturbation is always present and the dc coupling coefficient given by it changes along the grating, shifting local Bragg wavelengths. As a result, simply changing the magnitude of dielectric perturbation leads to incomplete apodization [8]. Therefore the apodization should be done under the condition that the dc dielectric perturbation is zero or near zero. This issue has already been overcome by introducing a phase shift between the two sidewall gratings or by changing the phase of the grating [9,10]. Both techniques rely on a modulation of the corrugation position, which leads to a change in the duty cycle. Fortunately, it appears that the dc coupling coefficient of these treated gratings is small compared with the ac coupling coefficient. Regarding the apodization based on the amplitude modulation, further research is required.

In this paper, we present a simple and efficient method for suppressing the sidelobes of CWGs based on the modulation of the corrugation depth. The apodized CWG (ACWG) is constructed only by forming the corrugation on both sides across the film-cladding boundary of the waveguide to minimize the dc coupling coefficient. The numerical simulation based on the CMT shows that the sidelobes can be suppressed to a practical level. The proposed apodization technique is suitable for the sidewall corrugation rather than for the surface corrugation for ease of fabrication.

2. Device structure and analysis

We consider a slab-waveguide model and the propagation of the fundamental TE_0 mode since a three-dimensional (3D) waveguide structure can be approximately replaced by a 2D structure using the equivalent index method. The CMT based on the 2D model is sufficient to examine the validity of the proposed apodization method. Fig. 1 shows three types of CWGs that are discussed in this paper. To shorten the length of the grating, the corrugation is symmetrically formed along both sides of the waveguide. If it is formed on one side, the coupling coefficients decrease by half. Two single-mode waveguides of width $2d$ and refractive index n_1 are connected to the grating section of length L. The grating structure proposed in this paper is the ACWG shown in Fig. 1(c). For the sake of completeness, the uniform CWG

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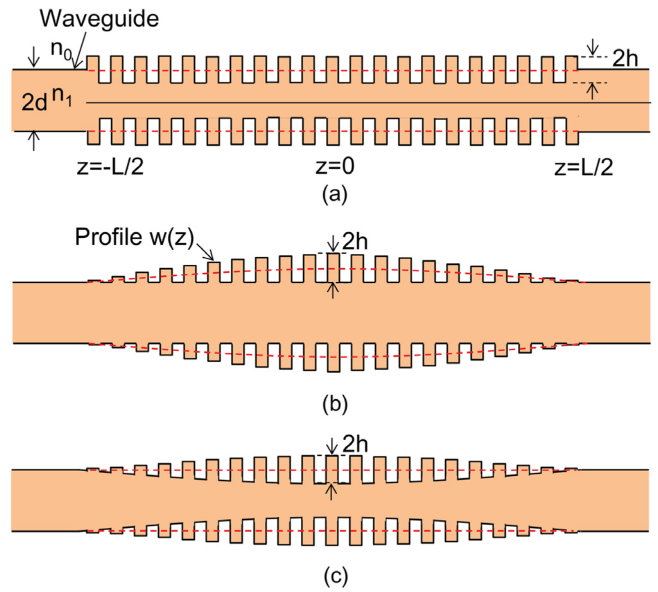

Fig. 1. Schematic of three kinds of CWGs; (a) uniform CWG, (b) conventional ACWG, and (c) proposed ACWG. The film-cladding boundaries of the unperturbed waveguide are drawn with red broken lines.

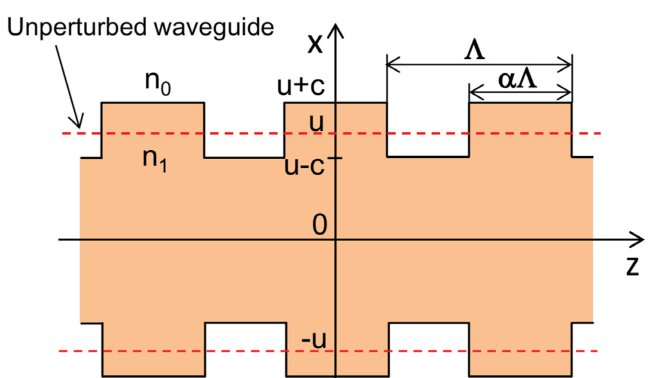

Fig. 2. Expanded grating structure and the coordinate system for the calculation of coupling coefficients. The film-cladding boundaries of the unperturbed waveguide are drawn with red broken lines.

and conventional ACWG shown in Fig. 1(a) and (b) are also taken into account.

To analyze the reflection properties of these CWGs, we employ the conventional CMT [7] that describes an interaction between a forward mode and an identical backward mode. We express the electric field of these two waves as $E_y^+ = a(z)\,F(x)\,e^{j(\omega t-\beta z)}$ and $E_y^- = b(z)\,F(x)\,e^{j(\omega t+\beta z)}$, where β and $F(x)$ are the propagation constant and the transverse field distribution of the TE_0 mode in the unperturbed waveguide, respectively. Here $F(x)$ is normalized so that the power flow in the z direction may become unity. When the synchronization condition is approximately satisfied ($\beta \approx \pi/\Lambda$, where Λ is the grating period), the change of the modal amplitudes $a(z)$ and $b(z)$ can be expressed as [7]

$$\begin{cases} \dfrac{da(z)}{dz} = -j\sigma a(z) - j\kappa b(z)\, e^{j2\delta z} \\ \dfrac{db(z)}{dz} = j\sigma b(z) + j\kappa a(z)\, e^{-j2\delta z} \end{cases} \tag{1}$$

where $\delta = \beta - \pi/\Lambda = \beta - \beta_D = \beta - \frac{2\pi}{\lambda_D} n_{eff}$ is the detuning from synchronism, λ_D is the design wavelength, n_{eff} is the effective mode index, σ is the dc coupling coefficient, and κ is the ac coupling

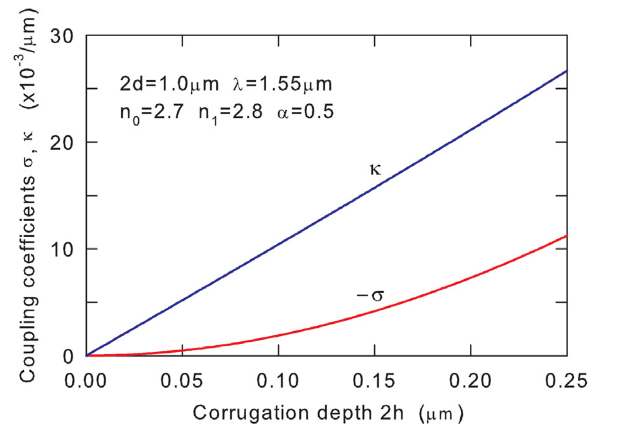

Fig. 3. Dependence of the coupling coefficients σ and κ on the corrugation depth $2h$ for the uniform CWG.

coefficient. These two coupling coefficients are given by

$$\sigma = \frac{\omega\varepsilon_0}{4}\int_{-\infty}^{\infty} \Delta\varepsilon_0(x)\, F(x)^2 dx \tag{2}$$

$$\kappa = \frac{\omega\varepsilon_0}{4}\int_{-\infty}^{\infty} \Delta\varepsilon_1(x) F(x)^2 dx \tag{3}$$

where $\Delta\varepsilon_0(x)$ and $\Delta\varepsilon_1(x)$ are the first (dc) and second (ac) terms in a Fourier series of the difference $\Delta\varepsilon(x,z)$ of the actual relative dielectric constant from the unperturbed distribution $\varepsilon(x,z)$. If the grating is uniform along z, closed-form solutions for Eq. (1) can be found when appropriate boundary conditions are specified. For the non-uniform gratings shown in Fig. 1(b) and (c), we can numerically solve the coupled-mode equations by a piecewise-uniform approach [11,12], where the grating is approximated by a number of uniform grating sections.

A closed-form expression for coupling coefficients σ and κ is required in the actual calculation. Fig. 2 shows the partly expanded grating structure. The corrugation depth is $2c$ and the duty cycle of the corrugation is α. Since the duty cycle will be set to 50% ($\alpha = 0.5$), we assume that the film-cladding boundaries of the unperturbed waveguide are located at the middle of the corrugation depth ($x = u$) [13], which are drawn with red broken lines in Figs. 1 and 2. For the gratings shown in Fig. 1(a) and (c), their unperturbed waveguides are the same as the input waveguide of width $2d$ (i.e., $u = d$). On the other hand, the boundary defined by $x = u$ is a function of the position z along the grating for the grating shown in Fig. 1(b). Note that the coupling coefficients depend on the choice of the unperturbed waveguide.

Under such an assumption, the perturbation $\Delta\varepsilon(x,z)$ can be written as

$$\Delta\varepsilon(x,z) = \Delta\varepsilon_0(x) + \Delta\varepsilon_1(x)\left(e^{j\frac{2\pi}{\Lambda}z} + e^{-j\frac{2\pi}{\Lambda}z}\right)$$
$$= \begin{cases} \left(n_1^2 - n_0^2\right)\left[\alpha - 1 + \dfrac{\sin(\alpha\pi)}{\pi}\left(e^{j\frac{2\pi}{\Lambda}z} + e^{-j\frac{2\pi}{\Lambda}z}\right)\right], & \text{for } u > x > u - c \\ \left(n_1^2 - n_0^2\right)\left[\alpha + \dfrac{\sin(\alpha\pi)}{\pi}\left(e^{j\frac{2\pi}{\Lambda}z} + e^{-j\frac{2\pi}{\Lambda}z}\right)\right], & \text{for } u + c > x > u \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where the half space $x > 0$ is considered for simplicity. When $\alpha = 0.5$, we have $\Delta\varepsilon_0(x) = -(n_1^2 - n_0^2)/2$ for $u > x > u - c$ and $\Delta\varepsilon_0(x) = (n_1^2 - n_0^2)/2$ for $u + c > x > u$. On the other hand, $\Delta\varepsilon_1(x) = (n_1^2 - n_0^2)/\pi$ for $u + c > x > u - c$. Therefore it is clear from Eqs. (2) and (3) that the dc coupling coefficient σ is smaller than the ac coupling coefficient κ. It is also found that the coefficient κ becomes maximum when $\alpha = 0.5$. When the corrugation depth $2c$ is small enough so that we can replace