Optical Power Transfer of Grating-Assisted Directional Coupler with Three-Guiding Channels: TM modes Case

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Abstract

The optical power transfer of TM modes in grating-assisted directional couplers (GADCs) with three-guiding channels is rigorously evaluated by defining a novel coupling efficiency amenable to the rigorous analytical solutions of modal transmission-line theory (MTLT). The results reveal that the incident power is sensitively partitioned through three output channels in terms of such grating parameters as the period, the duty cycle, and wavelength.

Key words : Grating-Assisted Directional Couplers, Coupling Efficiency, Field Orthogonality Condition

I. Introduction

The grating-assisted coupling structures are increasingly used for many applications in the field of photonics, especially, such as the power distribution for WDM and optical switching. Those couplers have so far been examined to explore the coupling efficiency between two rigorous or local normal modes in the context of two-guide grating coupler [1, 2], and proposed to improve the wavelength filtering performance only in the context of a three-guide grating coupler [3]. Although many applicable examples adopted these configurations have been presented, to the best of my knowledge the design characteristics of optical device served as power distributor and supported by the superposition of multi-modes as three-guide grating couplers, have been excluded.

In this paper, we thus propose a guided-wave device, that is designed by applying three-guide grating coupler of which center waveguide is corrugated with a periodic grating structure, for dividing the incident power into the desired ratio. This arrangement allows the power dividing characteristics to be superimposed on a more controllable way. Because the desired power distribution can be obtained easily by tuning the grating parameters. Consequently, we simply and explicitly treat the optical power distribution with the coupling efficiency between the input and output modal voltages of an equivalent transmission-line network, which is newly defined in this paper.

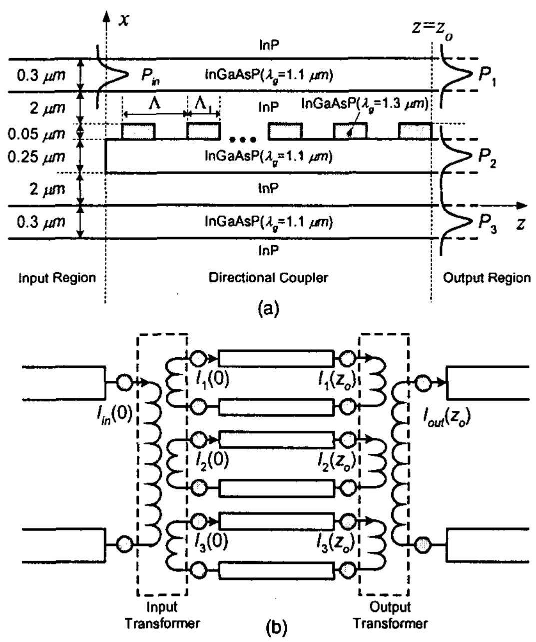


Fig. 1. (a) Schematic configuration of grating-assisted directional coupler (GADC) with three-guides, and (b) the equivalent transmission-line network corresponding to the three-guide GADC of Fig. 1(a).

The typical grating-assisted geometry with three-guiding channels applicable to the proposed approach is illustrated in Fig. 1 (a). As can see, the coupler has three-guides so that only three propagating rigorous modes have a significant meaning and dominate the power coupling of three-guide GADC, being described by three equivalent networks in coupling region as shown in Fig. 1 (b). Furthermore, InP/InGaAsP semiconductor materials operating in the range of optical frequency comprise the grating coupler, and their refractive indices are calculated by using single-effective-oscillator model [4].

II. Coupling Efficiency of TM Modes

When we evaluate the power dividing characteristics in three-guide GADCs, an interesting feature is the complete power transfer between the outside guides, which depends on the interaction of the three rigorous modes launching into the input boundary plane of coupling region. Such a behavior occurs if the propagation constants of the rigorous modes are equally spaced. That is, this is essentially similar to the situation to determine the maximum power transfer from one outermost guide to the other outermost guide in stratified three-guide coupler [5]. Simply stated, if the mode gaps are equally spaced, the phase difference between the adjacent two modes (that is, 1st-order symmetric and 2nd-order asymmetric modes) will be π. Subsequently, the next two higher-order modes (that is, 2nd-order asymmetric and 3rd-order symmetric modes) will be also π. Thus, the phase difference between two symmetric modes is zero so that the two symmetric modes and one asymmetric mode are phase matched as at two-guide couplers.

To clarify the validity in three-guide GADCs, all we have to do here is to determine the propagation constants of three rigorous modes generated at the composite corrugation structure pictured in Fig. 1. The complex eigenvalues $k_{zn} = k_{z0} + 2n\pi / \Lambda$ with $k_{z0} = \beta + i\alpha$ (where n and Λ represent the n-th space harmonic and the periodicity of grating, respectively) can be then calculated by applying the transverse resonance condition of MTLT [6]

$$\left|\mathbf{Y}_{up}\left(k_{zn}\right) + \mathbf{Y}_{dn}\left(k_{zn}\right)\right| = 0 , \qquad (1)$$

where $\mathbf{Y}_{up}\left(k_{zn}\right)$ and $\mathbf{Y}_{dn}\left(k_{zn}\right)$ indicate the admittance square matrices looking up and down at an arbitrary layer boundary on x-axis, respectively. The unknown eigenvalue k_{zn} is then related to all the functional quantities included in Eq. (1), and the three rigorous modes guided in three-guide GADC are determined by the eigenvalue problem. Once determined the quantity k_{zn}, the fields H and E of TM modes at any point (x, z) inside the periodic interval $0 \le z \le \Lambda$ are precisely defined by the following modal descriptions [1]

$$H_j^{\pm}(x,z) = I_o^{\pm} \sum_n h_{jn}^{\pm}(x) e^{\pm ik_{zn}z} , \qquad E_j^{\pm}(x,z) = \pm \frac{V_o^{\pm}}{\varepsilon_j(z)} \sum_n e_{jn}^{\pm}(x) e^{\pm ik_{zn}z} , \qquad (2)$$

where $I_o^{\pm}, V_o^{\pm}$ is the modal current and voltage related each other by the effective characteristic impedance of TM modes, and $h_{jn}^{\pm}(x)$, $e_{jn}^{\pm}(x)$ is the modal functions.

Then, we assume that a wave is incident into the upper guiding channel as shown in Fig. 1(a). For TM modes propagating in homogeneous stratified waveguides, that is, at the input (z<0) and the output (z>z_0) regions, the transverse magnetic H_y and electric E_x fields are expressed as [7]

$$H_\xi(x,z) = I_\xi(z) h_\xi(x),\ E_\xi(x,z) = V_\xi(z) e_\xi(x), \quad (3)$$

where the modal voltage V_ξ and current I_ξ are related by $V_\xi / I_\xi = k_{z,\xi} / (\omega\varepsilon_0)$ with the propagation constant $k_{z,\xi}$ designated ξ = *in* or *out* for the input or output region, respectively. Here, $e_\xi(x)$ and $h_\xi(x)$ denote the electric and magnetic modal functions in uniform stratified guides.

Then, if we neglect the reflections at the input and output junction boundaries, the total field in the grating-assisted coupling region can be written by a linear superposition of three propagating rigorous modes

$$H_c(x,z) = \sum_{\nu=1}^{3} \left\{ I_\nu(z) \sum_n h_{jn}^{(\nu)}(x) e^{i(2n\pi/\Lambda)z} \right\} , \qquad (4)$$

where the basis modal current is $I_\nu(z) = I_{0,\nu} e^{ik_{z0,\nu}z}$, for which the propagation constant $k_{z0,\nu} = \beta_\nu + i\alpha_\nu$ with ν=1, 2 or 3 designates the three lowest-order modes, and $h_{jn}^{(\nu)}(x)$ represents the spatial variation of n-th space harmonics along x-direction.

The field incident into the junction boundary z=0 from the upper guide generates the three rigorous modes, being guided by the periodic region where they propagate independently along the longitudinal z-direction. Then, the boundary conditions at z=0 with neglecting the facet reflections give us the following continuous condition happened between the input (homogeneous) and coupling (inhomogeneous) regions.

$$I_{in}(0)h_{in}(x) \cong \sum_{\nu=1}^{3}\left\{I_\nu(0)\sum_n h_{jn}^{(\nu)}(x)\right\} . \quad (5)$$

Then, performing cross-product in Eq. (5) with

$$\frac{1}{\varepsilon_j}\sum_r k_{zr,\nu}h_{jr}^{(\nu)}(x) \text{ for } k_{zr,\nu} = k_{z0,\nu} + \frac{2r\pi}{\Lambda} ,$$

and integrating over the cross section (cs) of guiding structure, the modal currents at input boundary satisfying the field orthogonality condition of TM modes defined in the literature [1] are found to be

$$I_\nu(0) = A_\nu I_{in}(0) , \quad (6)$$

where the input transformation constant A_ν is given by

$$A_\nu = \frac{1}{C_\nu}\int_{cs}\left\{\frac{h_{in}(x)}{\varepsilon_j}\sum_r k_{zr,\nu}h_{jr}^{(\nu)}(x)\right\} dS \quad (7)$$

with the appropriate normalization constant C_ν determined by the power normalized condition of three-guide GADC considered. The input transformation constant A_ν can be then thought as a voltage transformation ratio, referring to the amount of the incident voltage distributing to the equivalent voltages of three rigorous modes excited in the input terminal of three-guide GADC.

Consequently, the modal voltages orthogonal rigorous modes excited at the input interface (z=0) propagate along the longitudinal z-direction, and decay exponentially in terms of the leakage losses α_ν . Then, the boundary condition at the output terminal z=z_0 yields

$$I_{out}(z_0)h_{out}(x) \cong \sum_{\nu=1}^{3}\left\{I_\nu(z_0)\sum_n h_{jn}^{(\nu)}(x)e^{i(2n\pi/\Lambda)z_0}\right\} \quad (8)$$

which satisfies the continuity between the modal fields traveling at the coupling and output regions. Thus, applying the power normalization of output modal fields for stratified guiding structures

$$\int_{cs}\frac{1}{\varepsilon_j}h_{out}(x)h_{out}^*(x)\ dS = 1$$

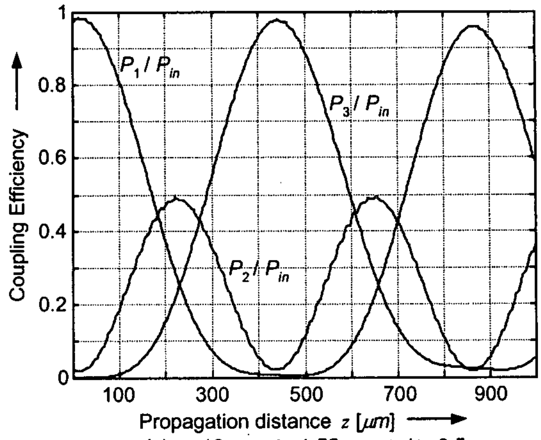
to Eq. (8), the output modal voltage $I_{out}(z_0)$ can be expressed as

$$\frac{I_{out}(z_0)}{I_{in}(0)} = \sum_{\nu=1}^{3}\left\{\ A_\nu B_\nu e^{ik_{z0,\nu}\ z_0}\right\} \equiv R_{TM} , \quad (9)$$

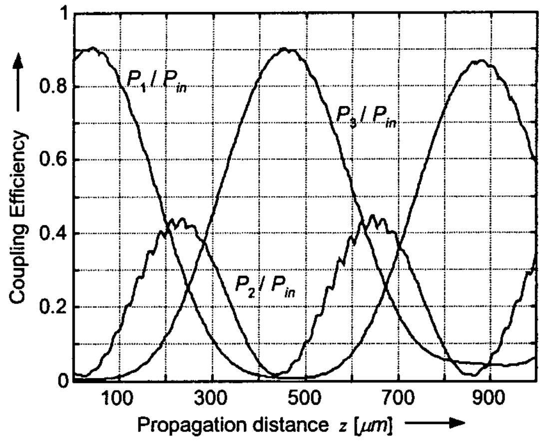
where R_{TM} describes the total transfer factor coupled between the input and output modal currents, and the output transformation coefficient B_ν with such a significant physical meaning as A_ν is

$$B_\nu = \int_{cs}\left\{\frac{h_{out}^*(x)}{\varepsilon_j}\sum_n h_{jn}^{(\nu)}(x)\ \ e^{i(2n\pi/\Lambda)z_o}\right\} dS .$$

The equivalent transmission-line network illustrating pictorially the electromagnetic analysis procedure presented above for three-guide GADC is depicted in Fig. 1(b). Using the modal mechanism of equivalent network, we can define a convenient and powerful formalism to analyze the power transfer of TM modes, which is called coupling efficiency η. The coupling efficiency is the ratio of the output power ($V_{out}I_{out}^*$) to the input power ($V_{in}I_{in}^*$), which yields



(a) Λ=16 μm , λ=1.55 μm, Λ_1/Λ=0.5



(a) Λ=24 μm , λ=1.55 μm, Λ_1/Λ=0.5

Fig. 2. Variation of coupling efficiency along the propagation distance (a) at the phase-matching condition $\Lambda = 16\ \mu m$, and (b) at an arbitrary value $\Lambda = 24\ \mu m$.

$$\eta_{TM} = \frac{P_{out}}{P_{in}} = \frac{\mathrm{Re}(k_{z,out})}{\mathrm{Re}(k_{z,in})} |R_{TM}|^2 , \qquad (10)$$

III. Numerical Results and Discussions

To search the power transfer characteristics between two outside guides, it assumes that TM mode, whose power is normalized with 1 [Watt], is fed through the upper guide at the input terminal. After propagating over an arbitrary distance z_o of the coupler, the field is emitted through the guiding channels at the output terminal.

The output power at the beat lengths, satisfying a phase-matching condition $2\beta_2 - \beta_1 - \beta_3 = 0$, is then maximized or minimized according to the outside guides. Such a behavior is illustrated in Fig. 2(a). As a consequence of the phase-matching condition depicted at Fig. 2(a), we can observe that the power flow between two outside guides is periodic and P_1 / P_{in} attains zero at the coupling length $z_o = 432\ \mu m$ so that P_3 / P_{in} is maximized at the point. That is, the power transfer over 98% between the outside guides occurs. Moreover, the magnitude P_2 / P_{in} of power flow in center guide is, as expected, almost zero, though being seen a little bit fluctuation via the discontinuity of grating facets. It can thus know that the phase-matching condition proposed first at the three-guide stratified couplers [5] hold well even in the three-guide GADCs.

An interesting result calculated numerically with a value detuning from phase-matching condition, that is, at out of phase-matching condition ($2\beta_2 - \beta_1 - \beta_3 \neq 0$), is plotted in Fig. 2(b). Figure 2(b) shows that the variation of such a grating parameter as periodicity Λ significantly affects in the power transfer between the outside guides. As shown in the figure, about 85% of power incident through the upper guide is coupled to the lower guide at a propagation length $z_o = 432\ \mu m$.

Finally, the effects of wavelength λ and aspect ratio Λ_1 / Λ are examined. The numerically calculated coupling efficiency is displayed in Fig. 3. Similarly to the result in phase-matching condition as shown in Fig. 3(a), the power transfer between the outside guides is over 98%, except that the coupling length shifts about 37% to the propagating z-direction. This implies that the device will serve as a broadband filter because the coupling efficiency of three-guide GADC is not sensitive to the variation of wavelength.

On the contrary, the power distribution at the output guides is extremely sensitive to the detuning values of aspect ratio. As shown in Fig. 3(b), the power transfer between the outside guides deteriorates below about 90% at a length $z_o = 442\ \mu m$. In addition, non-periodicity of power transfer corresponding to a further increase of propagation distance is observed. This is attributed to the fact that a destructive coupling between three rigorous modes occurs due to the asymmetric profile of grating.

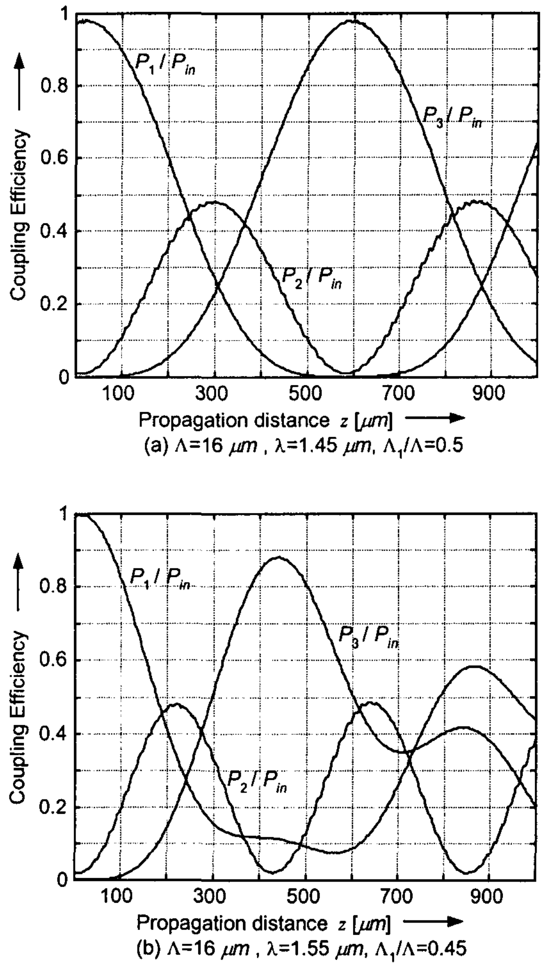


Fig. 3. Variation of coupling efficiency along the propagation distance (a) at a wavelength, and (b) at an aspect ratio different from phase-matching condition.

IV. Conclusions

Grating-assisted coupler with three-guiding channels, which serves as a power divider at optical communication system, is investigated. To analyze rigorously the power distribution (that is, the coupling efficiency) for TM modes, an equivalent network is used and it is based on newly developed field orthogonality condition and modal transmission-line theory. The numerical results reveal that the three-guide GADCs behave similarly to the three-guide stratified couplers regarding the complete power transfer between the outside guides at the phase-matching condition of three rigorous modes.

Consequently, it has found that the incident power is controllable to get the power transfer desired at output guiding channels, provided that such grating parameters as period, and aspect ratio is appropriately and numerically determined.

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