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

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

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I. INTRODUCTION

Stratified guiding structures with three guides have been theoretically explored and proposed as optical power dividers [1,2] in the design of planar guided waves for optical communication systems. In general, it consists of a directional coupler or Y-junction profile [3]. Y-junction is suitable as an optical power divider insensitive to the input optical wavelength, but the distribution of the incoming optical field is disturbed in a severe way because of the radiation loss incurred inherently at bends and the discontinuity at the Y-junction. Especially when the branching angle is large, the disadvantage is relatively high.

On the other hand, the parallel directional coupler with three guides offers great flexibility in power dividing. Because the radiation loss of the coupler is almost zero in the coupling region, and if we appropriately adjust the interaction length of the coupling region, the output power can be divided as a desired ratio. Although the three-guide coupler is a very low loss optical power divider and is easily utilized to exchange optical power between the composite waveguides, it is not suitable to use as a power divider for dense wavelength division multiplexing (DWDM) in optical communication because there is a disadvantage to implement wavelength selectivity.

One way to overcome those disadvantages is to use a combination of stratified directional coupler and periodic corrugation structure called grating-assisted directional coupler (GADC). The grating-assisted coupling structures are increasingly used for many applications in the field of photonics, especially, such as optical 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 a two-guide grating coupler [4,5], and have been proposed to improve only the wavelength filtering performance in the context of a three-guide grating coupler [6] except for the design characteristics of the power distributor which are supported by the superposition of multi-modes.

In this paper, we thus propose a guided-wave device, that is designed by applying a three-guide grating coupler of which the center waveguide is corrugated with a periodic grating structure, for dividing the incident power into the desired ratio and even into three equal portions. This arrangement allows the power dividing characteristics for TM modes to be superimposed in 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

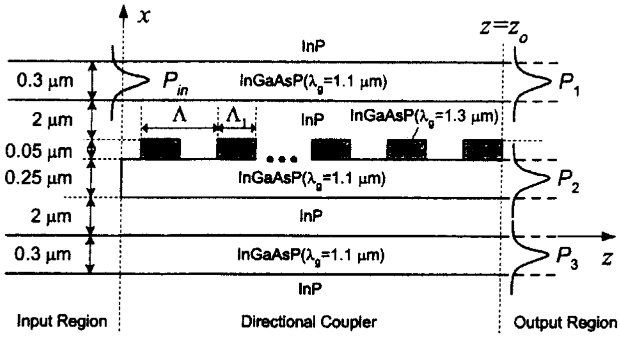


FIG. 1. Schematic configuration of grating-assisted directional coupler (GADC) with three-guides.

modal voltages, which is newly defined in this paper. As will be discussed in detail later, it can be achieved by an equivalent transmission-line network composed nominally to distribute the incident power through the output guiding channels in optical GADCs with three-guides.

The typical grating-assisted geometry with three-guiding channels applicable to the proposed approach is illustrated in Fig. 1. As can be seen, the coupler has three-guides so that only three propagating rigorous modes have a significant meaning and dominate the power coupling of the three-guide GADC, being described by three equivalent networks for TM modes in the coupling region as will be shown in Fig. 2. 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 [7].

II. FIELD ORTHOGONALITY CONDITIONS OF TM MODAL FUNCTIONS

In general, the guided-wave problems of GADCs require solving an eigenvalue problem and finding the basic propagation constant k_{z0}, which is unknown and defined in Eq. (7). If the unknown cmponent k_{z0} is well determined from the transverse resonance condition of Eq. (18), we can obtain all the modal field solutions satisfying the boundary conditions at each interface of the multi-layered grating structure.

These general solutions acquired are then utilized to explore the optical characteristic of GADCs, such as the power distribution due to transverse field variations in layers. However, to analyze rigorously the powers coupled and distributed at multi-layered periodic devices with different cross-sections cyclically along the longitudinal z-direction, we need to define novel modal characteristics. Most significant one among those modal characteristics is the field orthogonality condition of modes propagating in GADCs. Therefore, here we mathematically formulate these concepts containing the novel aspects of periodic structures based on the modal field representations for TM modes.

For two-dimensional ($\partial/\partial y \equiv 0$) situations and electromagnetic fields with time dependence $e^{-i\omega t}$, as will be assumed throughout this paper, the scalar transverse (to z-axis) field equations for a subset ($H_x=H_z=E_y=0$) of TM modes are given by

$$\frac{\partial H_y}{\partial z} = i\omega\varepsilon_o\varepsilon_j(z)E_x, \tag{1}$$

$$\frac{\partial E_x}{\partial z} = \frac{i}{\omega\varepsilon_o\varepsilon_j(z)}\left[k_o^2\varepsilon_j(z)+\frac{\partial^2}{\partial x^2}\right]H_y. \tag{2}$$

where μ_o and ε_o are the permeability and permittivity in vacuum, respectively, and $\varepsilon_j(z)$ is the periodic dielectric constant expressed as

$$\varepsilon_j(z) = \begin{cases} \varepsilon_j & \text{for } j \neq p \\ \sum_n \varepsilon_n e^{i(2n\pi/\Lambda)z} & \text{for } j = p \end{cases} \tag{3}$$

for homogeneous ($j \neq p$) regions and the inhomogeneous ($j = p$) region. The transverse magnetic field H_y in the multi-layered periodic media satisfying Eqs. (1) and (2) can be then written as

$$H_j = \sum_n Q_{jn}(x)e^{ik_{zn}z},$$
$$E_j = \frac{1}{\omega\varepsilon_o\varepsilon_j(z)}\sum_n k_{zn}Q_{jn}(x)e^{ik_{zn}z}, \tag{4}$$

where j represents the j-th layer on transverse x-axis in the guiding structure, the summations range over all integers n=0, ±1, ±2, ..., and the transverse field component is

$$Q_{jn}(x) = \begin{cases} y_{jn}(f_{jn}e^{ik_{jn}x}+g_{jn}e^{-ik_{jn}x}) & \text{for } j \neq p \\ \sum_m y_{jm}(f_{jm}e^{ik_{jm}x}+g_{jm}e^{-ik_{jm}x})\, b_{nm} & \text{for } j = p \end{cases}. \tag{5}$$

with the characteristic admittances

$$y_{jn} = \frac{\omega\varepsilon_o\varepsilon_j}{k_{jn}},\ y_{pm} = \frac{\omega\varepsilon_o}{k_{pm}\gamma_p} \tag{6}$$

for TM modes at the transverse x-direction, where γ_p is denoted the average of $1/\varepsilon_p(z)$. The quantities k_{pm} and b_{nm} stand for the characteristic values that satisfy the nonhomogeneous Helmholtz equation inside the periodic region. These values can be determined analytically [8] for all gratings whose periodic variation is independent on the x-axis. Here, the longitudinal and transverse propagation constants of Eqs. (4) and (5) are defined as

$$k_{zn} = k_{z0} + \frac{2n\pi}{\Lambda} \quad \text{with } k_{z0} = \beta + i\alpha ,$$

$$k_{jn} = \sqrt{k_0^2 \varepsilon_j - k_{zn}^2} \quad \text{for all } j \neq p , \tag{7}$$

where Λ stands for the periodicity of the grating as shown in Fig. 1.

Subsequently, the fields H_j or E_j of Eq. (4) may be expanded in terms of the complete set of modal magnetic function $h_{jn}^{\pm}(x)$ and current amplitude $I_o^{\pm}$, or modal electric function $e_{jn}^{\pm}(x)$ and voltage amplitude $V_o^{\pm}$ of each space harmonic, which yields

$$H_j^{\pm}(x,z) = I_o^{\pm} \sum_n h_{jn}^{\pm}(x) e^{\pm i k_{zn} z} ,$$

$$E_j^{\pm}(x,z) = \pm \frac{V_o^{\pm}}{\varepsilon_j(z)} \sum_n e_{jn}^{\pm}(x) e^{\pm i k_{zn} z} , \tag{8}$$

Since the modal descriptions above should be equivalent to Eq. (4), the field components and the modal solutions at the periodically symmetric planes are related each other by

$$Q_{jn}^{\pm}(x) = I_o^{\pm} h_{jn}^{\pm}(x) ,$$

$$e_{jn}^{\pm}(x) = \frac{Y_{ef}^{\pm}}{\omega \varepsilon_o} k_{zn} h_{jn}^{\pm}(x) ,$$

where $Y_{ef}^{\pm} = \pm(I_o^{\pm}/V_o^{\pm})$ is the effective characteristic admittance of the periodic guiding structures, which is inversely proportional to the normalization constant of the field orthogonality condition [4]. Then, applying Eqs. (8) to Eq. (2), and comparing the forward propagating modal function with the backward one gives

$$e_{jn}^{\pm}(x) = e_{jn}^{-}(x), \; h_{jn}^{+}(x) = -h_{jn}^{-}(x) , \tag{9}$$

which are useful and significant identities to define the field orthogonality condition for TM modes. Strictly speaking, Eq. (9) does not hold generally in periodic guides. However, if we choose a symmetric accessible plane in which field components are independent of the variation of $\varepsilon_j(\pm z)$, like uniform stratified guides, the equalities are true.

Then, the scalar equation of Eq. (1) can rewrite as

$$E_{j,(p,q)} = -\frac{i}{\omega \varepsilon_o \varepsilon_j(z)} \frac{\partial H_{j,(p,q)}}{\partial z} \tag{10}$$

for transverse p-th and q-th modes. Consequently, applying Eq. (10) to the Lorentz reciprocity theorem [1] for the general class of planar waveguides, we obtain

$$\int_0^{\Lambda} \int_{cs} \gamma_j(z) \sum_n \sum_r (k_{zn,p}^2 - k_{zr,q}^2) h_{jn,p}^2(x) h_{jr,q}^2(x) e^{i(k_{zn,p}+k_{zr,q})z} dS dz = 0 , \tag{11}$$

where $\gamma_j(z)=1/\varepsilon_j(z)$. After integrating over the unit-cell length $(0 \leq z \leq \Lambda)$, it reduces to

$$\int_{cs} \gamma_j \sum_n \sum_r (k_{zn,p} - k_{zr,q}) h_{jn,p}^{+}(x) h_{jr,q}^{+}(x) dS = 0 . \tag{12}$$

Note that, provided $k_{zn,p} \neq k_{zr,q}$, this implies that the above integral must be zero. Here the inverse dielectric constant γ_j independent on z-variation is

$$\gamma_j = \begin{cases} 1/\varepsilon_j & \text{for } j \neq p \\ 1/\sum_n \varepsilon_n & \text{for } j = p \end{cases} .$$

Now the forward-travelling mode $H_{j,q}^{+}$ is arbitrary so that it can be replaced it with any other mode, say a backward-travelling mode $H_{j,q}^{-}$. Then, applying this backward q-th mode and the forward p-th mode given in Eq. (10) to the Lorentz reciprocity theorem, it results in a solvable form of

$$\int_{cs} \gamma_j \sum_n \sum_r (k_{zn,p} + k_{zr,q}) h_{jn,p}^{+}(x) h_{jr,q}^{-}(x) dS = 0 . \tag{13}$$

Similarly to Eq. (14), if $k_{zn,p} \neq k_{zr,q}$, the above integrand must be zero. Thus, using the equality between the forward and backward magnetic modal functions defined in Eq. (9), and adding Eqs. (14) and (15), we have the orthogonality condition between two modes propagating along multi-layered periodic guides

$$\int_{cs} \gamma_j \sum_n \sum_r k_{zn,p} h_{jn,p}^{+}(x) h_{jr,q}^{+}(x) dS = 0 , \tag{14}$$

On the contrary, if $k_{zn,p} = k_{zr,q}$, it reduces to a normalized eigensolution as follows:

$$\int_{cs} \gamma_j \sum_n \sum_r k_{zn,p} h_{jn,p}^{+}(x) h_{jr,q}^{+}(x) dS = C_p , \tag{15}$$

where C_p represents a normalization constant for TM modes. In the following section, these field orthogonality conditions, given in Eqs (16) and (17), will be used to explore rigorously the power transfer of TM modes between three guiding channels.

III. 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 the 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 a stratified three-guide coupler [9]. Simply stated, if the mode gaps are equally spaced, the phase difference between the adjacent two modes (that is, 1^{st}-order symmetric and 2^{nd}-order asymmetric modes) will be π. Subsequently, the next two higher-order modes (that is, 2^{nd}-order asymmetric and 3^{rd}-order symmetric modes) will be also π. Thus, the phase difference between two symmetric modes is zero so that the phases of three supermodes are 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 the grating, respectively) can be then calculated by applying the transverse resonance condition of MTLT [8]

$$\left|Y_{up}(k_{zn}) + Y_{dn}(k_{zn})\right| = 0, \quad (16)$$

where $Y_{up}(k_{zn})$ and $Y_{dn}(k_{zn})$ 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. (18), and the three rigorous modes guided in three-guide GADC are determined by the eigenvalue problem. Once the quantity k_{zn} is determined, 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 modal transmission-line descriptions as mentioned in Eq. (8).

Then, we assume that a wave is incident into the upper guiding channel as shown in Fig. 1. 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 [10]

$$H_\xi(x,z) = I_\xi(z)h_\xi(x),\ E_\xi(x,z) = V_\xi(z)e_\xi(x), \quad (17)$$

where the modal voltage V_ξ and current I_ξ are related by

$$\frac{V_\xi}{I_\xi} = \frac{k_{z,\xi}}{\omega\varepsilon_o}$$

with the propagation constant $k_{z,\xi}$ designated $\xi = in$ 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

$$H_c(x,z) \cong \sum_{\nu=1}^{3}\left\{I_\nu(z)\sum_n h_{jn}^{(\nu)}(x)e^{i(2n\pi/\Lambda)z}\right\}, \quad (18)$$

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 $\nu = 1$, 2 or 3 designates the three lowest-order modes, and $h_{jn}^{(\nu)}(x)$ represents the spatial variation of n-th space harmonics along the 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 $z=0$ give us the following identity happening at the interface of the input (homogeneous) and coupling (inhomogeneous) regions

$$I_{in}(0)h_{in}(x) \cong \sum_{\nu=1}^{3}\left\{I_\nu(0)\sum_n h_{jn}^{(\nu)}(x)\right\}. \quad (19)$$

Then, performing cross-product in both sides of Eq. (22) with

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

and integrating over the cross section (cs) of the guiding structure, the modal currents at an input boundary satisfying the field orthogonality condition, given in Eqs (16) and (17), for TM modes are found to be

$$I_\nu(0) = A_\nu I_{in}(0), \quad (20)$$

where the input transformation constant A_ν is given by

$$A_\nu = \frac{\gamma_j}{C_\nu}\int_{cs}\left\{h_{in}(x)\sum_r k_{zr,\nu}h_{jr}^{(\nu)}(x)\right\}dS \quad (21)$$

with the appropriate normalization constant C_ν determined by the power normalized condition of the three-guide GADC being considered. The input transformation constant A_ν can be then thought of 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 the three-guide GADC.

Consequently, the 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

$$I_{out}(z_0)h_{out}(x) \cong \sum_{v=1}^{3}\left\{I_v(z_0)\sum_n h_{jn}^{(v)}(x)e^{i(2n\pi/\Lambda)z_0}\right\}, \quad (22)$$

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

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

to Eq. (25), the output modal voltage $I_{out}(z_0)$ can be expressed as

$$\frac{I_{out}(z_0)}{I_{in}(0)} = \sum_{v=1}^{3}\left\{A_v B_v e^{ik_{z0,v}z_0}\right\} \equiv R_{TM}, \quad (23)$$

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

$$B_v = \gamma_j \int_{cs}\left\{h_{out}^*(x)\sum_n h_{jn}^{(v)}(x)e^{i(2n\pi/\Lambda)z_0}\right\}dS$$

The equivalent transmission-line network illustrating pictorially the electromagnetic analysis procedure presented above for three-guide GADC is depicted in Fig. 2. 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

$$\eta_{TM} = \frac{P_{out}}{P_{in}} = \frac{\mathrm{Re}(k_{z,out})}{\mathrm{Re}(k_{z,in})}|R_{TM}|^2 \quad (24)$$

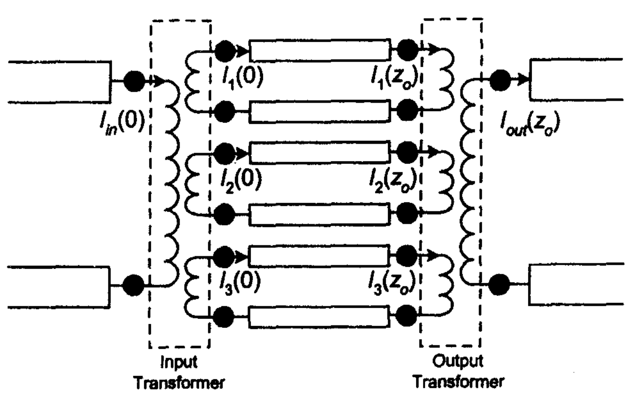


FIG. 2. Equivalent transmission-line network corresponding to the three-guide GADC of Fig. 1.

IV. NUMERICAL RESULTS AND DISCUSSIONS

To search the power transfer characteristics between two outside guides, it assumes that the TM mode, whose power is normalized to 1 [Watt], feeds 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.

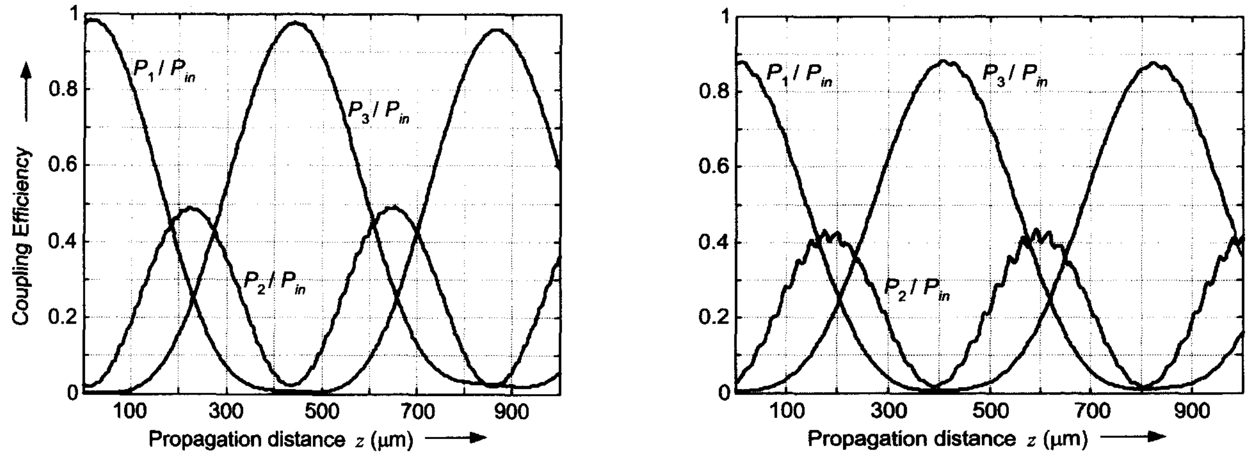
The output power at the beat lengths, satisfying a phase-matching condition $2\beta_2 - \beta_1 - \beta_3 = 0$, is then maximized or minimized according to the outside guides. Such a behavior is illustrated in Fig. 3. As a consequence of the phase-matching condition. the figure 3 (a) shows that the power flow between two outside guides is periodic and P_1/P_{in} attains zero at the coupling length $z_o \approx 432$ μm so that P_3/P_{in} is maximized at the point. That is, the power transfer of 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 a little bit fluctuation is seen via the discontinuity of grating facets. It can thus be seen that the phase-matching condition proposed first at the three-guide stratified couplers [6] holds well even in the three-guide GADCs.

An interesting result calculated numerically with a value detuning from the phase-matching condition, that is, at out of phase-matching condition ($2\beta_2 - \beta_1 - \beta_3 \neq 0$), is plotted in Fig. 3 (b). Figure 3 (b) shows that the variation of such a grating parameter as periodicity Λ significantly affects the power transfer between the outside guides. As shown in the figure, about 87% of power incident through the upper guide is coupled to the lower guide at a propagation length $z_o \approx 400$ μm.

Furthermore, the coupling characteristic of optical powers along the variation of wavelength λ and aspect ratio Λ_1/Λ is examined. The coupling efficiency calculated numerically at a detuning wavelength ($\lambda = 1.45$ μm) is displayed in Fig. 4 (a). Similarly to the result in phase-matching condition as shown in Fig. 4 (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 the three-guide GADC is not sensitive to the variation of wavelength.

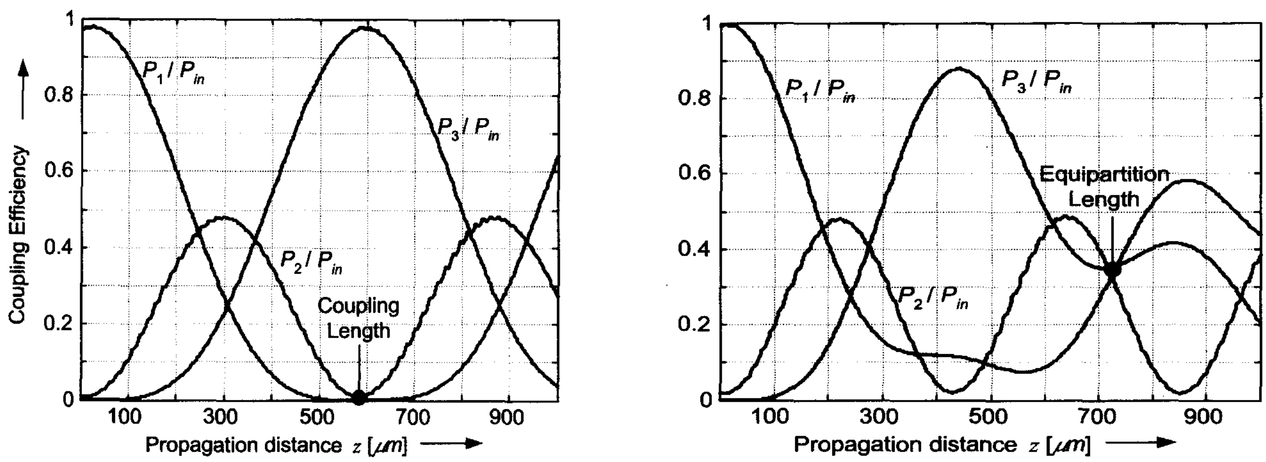
On the contrary, the power distribution at the output guides is extremely sensitive to the detuning values of aspect ratio. As shown in Fig. 4 (b), the power transfer between the outside guides deteriorates below about 90% at a length $z_o \approx 442$ μm. However, the incident power is partitioned equally into each output guide with about 33% power near an equal partition length $z_o \approx 720$ μm.

Consequently, those results reveal that the coupling



(a) Λ=16 μm, λ=1.55 μm, Λ_1/Λ=0.5 (b) Λ=26 μm, λ=1.55 μm, Λ_1/Λ=0.5

FIG. 3. Variation of coupling efficiency along the propagation distance (a) at the phase-matching condition Λ=16 μm and (b) at an arbitrary value Λ=26 μm.



(a) Λ=16 μm, λ=1.45 μm, Λ_1/Λ=0.5 (a) Λ=16 μm, λ=1.55 μm, Λ_1/Λ=0.45

FIG. 4. Variation of coupling efficiency along the propagation distance (a) at a wavelength, and (b) at an aspect ratio different from phase-matching condition.

length and equi-partition length can be determined just by adjusting the geometrical length of GADC with the optical parameters of grating-assisted couplers such as the grating period, the duty cycle, and the operating wavelength.

V. CONCLUSION

Grating-assisted couplers with three guides are investigated to serve as an optical power divider for an optical communication system. To analyze rigorously the power distribution (that is, the coupling efficiency) for TM modes, an equivalent network is used and it is based on a 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. Furthermore, the coupler is designed so as to operate under a specific situation, that is, to emit the incident optical power into three equal parts. Consequently, it has been found that the incident power is equally distributed at the output guiding channels, provided that such grating parameters as the grating period, the duty cycle, and the operating wavelength are appropriately and numerically determined.

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