Design of Optical Filters using Grating-Assisted Fiber Couplers (GAFCs)

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Abstract: This paper first takes advantage of a rigorous modal transmission-line theory (MTLT) to analyze the filtering properties of optical waves guiding by grating-assisted fiber couplers (GAFCs). The numerical results reveal that MTLT serves as a suitable and powerful approach to evaluate systematically the dispersion properties and the characteristics of optical power transfer in GAFCs.

1. INTRODUCTION

Grating-assisted directional couplers (GADCs) have been interested as crucial devices for selective wavelength filtering [1] and multi-channel data transmission [2] due to the wide wavelength tuning ability in optical communication. The optical characteristics supported by power coupling between even (symmetric) and odd (anti-symmetric) modes mainly have been investigated in GADCs of planar guiding type. However, the planar grating configuration is not suitable to implement an efficient linking between optical fiber devices, which is risen in many fiber communication systems.

To solve this problem, in this paper we propose a grating-assisted fiber coupler (GAFC) in which single mode fiber is directionally coupled to a planar thin-film guide with grating, as shown schematically in Fig. 1. The single mode fiber consists of core and cladding with refractive index $n_{cd} = 1.44$ and $n_{co} = 1.46$ at an operating wavelength $\lambda = 1.55\,\mu m$, and the thickness of core is selected as $t_{co} = 4\,\mu m$. The single mode fiber is then coupled to an $t_f = 1\,\mu m$ thick aluminum oxide (Al_2O_3) thin-film of refractive index 1.6 coated on silica dioxide (SiO_2) of refractive index 1.447.

In addition, to transfer efficiently the power between two dissimilar waveguides (fiber and film with grating), we remove the fiber cladding by polishing tangentially to the core of fiber.

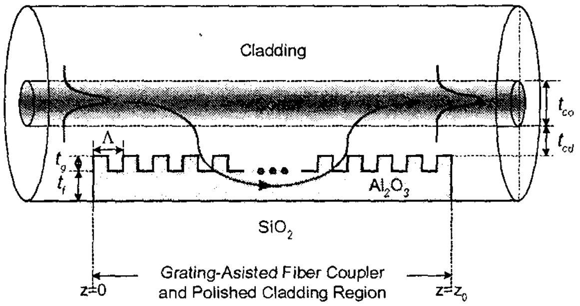

Fig. 1. Schematic configuration of grating-assisted fiber coupler (GAFC).

Consequently, to design a GAFC with narrowband filter response, we numerically evaluate the coupling efficiency of GAFC by using modal transmission-line theory developed newly by Ho *et al.* [3] and based on the transverse resonance technique of equivalent network approach [4].

2. FILTERING PROPERTIES OF GAFCS

For the composite corrugation structure pictured in Fig. 1, the complex propagation constant (eigenvalues) $k_{zn}=k_{zo}+2n\pi/\Lambda$ with $k_{zo}=\beta+i\alpha$ (where n and Λ represent the space harmonics and the periodicity of grating, respectively) can be calculated by applying the transverse resonance condition of equivalent network approach [4]

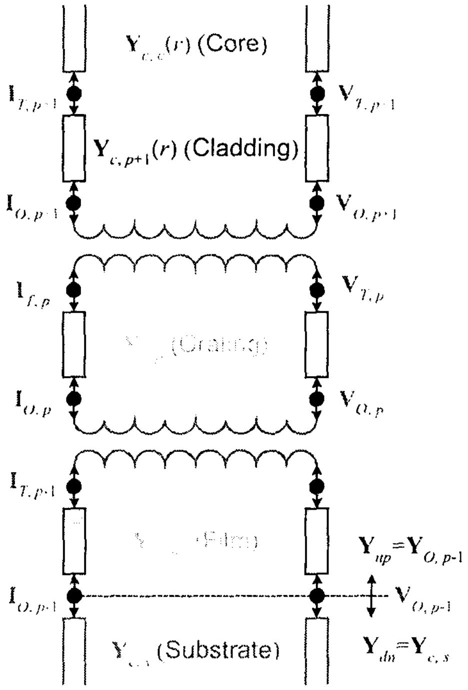

Fig. 2: Equivalent transmission-line network for GAFC of Fig. 1 on the transverse direction.

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

where $\mathbf{Y}_{up}$ and $\mathbf{Y}_{dn}$, as shown in Fig. 2, indicate the admittance square matrices looking up and down at an arbitrary j-th layer boundary on transverse direction, respectively, and each modal factor at the interfaces between grating layers is related to the characteristic values $\mathbf{A}$, $\mathbf{B}$ [4] of modal fields satisfying the wave equations inside the periodic region as follows:

$$\mathbf{V}_{T,p-1}=\mathbf{A}\mathbf{V}_{O,p}\ ,\quad \mathbf{I}_{T,p-1}=\mathbf{B}\mathbf{I}_{O,p}\ ,$$

$$\mathbf{A}\mathbf{V}_{T,p}=\mathbf{V}_{O,p+1}\ ,\quad \mathbf{B}\mathbf{I}_{T,p}=\mathbf{I}_{O,p+1}\ .$$

The unknown eigenvalue k_{zn} is then related to all the functional quantities included in Eq.(1), and the rigorous modes guided in GAFC are evaluated from the dispersion relation given as the result of Eq.(1). Once determined the quantity k_{zn} , the fields E and H of the pertinent propagating waves at any point (x, z) inside the periodic interval $0\leq z\leq z_o$ can be precisely defined for homogeneous regions and for periodic regions.

Now, using the exact eigenvalue k_{zo} obtained above, we analyze numerically the dispersion curves of the two modes propagating in the GAFC as a function of grating period Λ. Such a behavior is shown in Fig. 2. When a homogeneous layer replaces the grating region with permittivity ε_g being the average of the grating variation

$$\varepsilon(z)=\sum_n \varepsilon_n e^{\frac{2n\pi}{\Lambda}z}\ , \qquad (2)$$

the guiding structure supports two orthogonal surface-wave modes (supermodes or composite modes) with effective refractive indices N_{ev} and N_{od} , respectively. If periodicity Λ is introduced at a desired operating

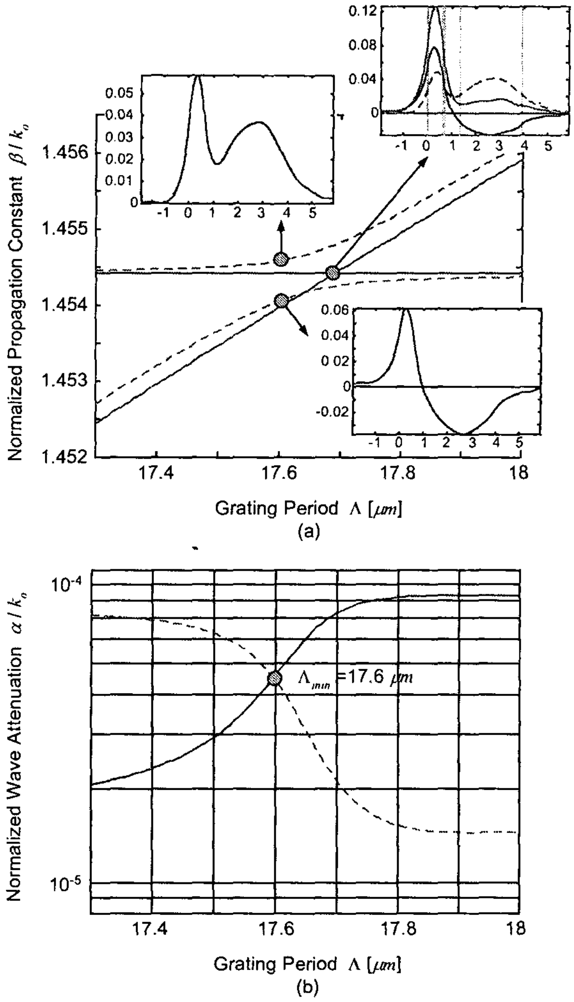

Fig. 3: Complex propagation constant of the two guiding modes. (a) Propagation constant of the two surface-wave and leaky-wave modes and (b) attenuation constant of the two modes. Here the grating depth is t_g=0.1 μm, and the fields inserted in Fig. 2(a) are the real parts of the rigorous modes.

wavelength λ=1.55 μm, the curves for N_{ev} and $N_{od}-\lambda/\Lambda$ intersect at a phase-matching point (Λ_{ph}=17.69 μm) as shown in the solid-lines of Fig. 3. However, by the presence of periodicity, the surface-wave modes defined by N_{ev} and N_{od} is replaced by rigorous leaky-wave mode-pairs β_1 and β_2 (dashed-lines), which is generally subject to leakage losses occurred from Eq. (1)

This rigorous modal approach reveals that the narrowest value Λ_{min} of this $|(\beta_1-\beta_2)/k_o+\lambda/\Lambda|$ gap does not locate at $\Lambda=\Lambda_{ph}$ and occurs at a grating period Λ_{min}=17.6 μm whose value is smaller than that of Λ_{ph}. Consequently, the strong power transfer between the single mode fiber and the thin-film with grating occurs at the place where the field distributions of two modes are similar, as shown in the insets of Fig. 3.

Next, to clarify the validity of our results acquired in Fig. 3, we explore the power transfer between the two dissimilar waveguides of GAFC. Throughout this paper, we assume that the geometry is two-dimensional $\partial/\partial y=0$, and a fundamental TE mode is incident into the single mode fiber and is transmitted through the fiber. Then, the fiber mode excites even and odd modes propagating along z-direction at the input interface (z=0) of GAFC.

For TE modes, the transverse modal fields in input ($z<0$) and output ($z>z_o$) fibers, which are organized nominally to address the power coupling between two coupled waveguides, can be expressed by the transmission-line modal functions [6]

$$rE_\phi(r,z)=V(z)e(r)\ ,\ H_z(r,z)=I(z)h(r) \qquad (3)$$

where V and I, which represent the modal voltage and current respectively, are related by

$$\frac{V}{I}=\frac{\omega\mu}{\kappa}r\ .$$

In general, the guiding modes in optical coupler ($0\leq z\leq z_o$) are composed by the summation of the p-th discrete spectrum rather than continuous one of the surface waves

$$E(x;r,z)=\sum_p V_p(z)e_p(x;r)\ . \qquad (4)$$

However, in most practical cases, only a few such modes (often, only two modes in optical couplers with two guiding structures) have the physical meanings. The field components in this coupler can be obtained from a linear superposition of two significant modes, which is called *supermodes*

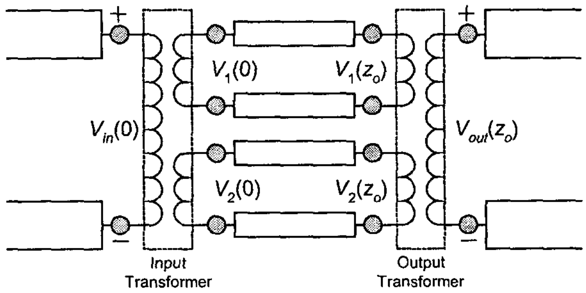

Fig. 4: Equivalent transmission-line network for GAFC of Fig. 1 on the longitudinal direction.

$$E_c(x;r,z)=V_1e^{ik_1z}\sum_n e_{jn}^{(1)}(x;r)e^{i\Lambda_n z}$$
$$+V_2e^{ik_2z}\sum_n e_{jn}^{(2)}(x;r)e^{i\Lambda_n z}\ , \qquad (5)$$

where the propagation constant $k_{zo,v}=k_v=\beta_v+i\alpha_v$ with v=1 or 2 designates the two lowest-order modes and the periodicity of space harmonics is $\Lambda_n=2n\pi/\Lambda$, and $e_{jn}^{(v)}(x;r)$ is the spatial variation of E_j along x-direction.

A modal field incident into the junction boundary $z=0$ from the lower waveguide generates supermodes that propagate independently along z-direction. The amplitudes of these supermodes decay or grow exponentially due to the loss or gain in the guiding structures, and is transmitted through the upper and/or lower channel at $z=z_o$. Eventually, using the boundary conditions at $z=0$ and neglecting reflections, we obtain the following identities

$$V_{in}(0)e_{in}(r)\cong V_1(0)\sum_n e_{jn}^{(1)}(x;r)+V_2(0)\sum_n e_{jn}^{(2)}(x;r)\ , (6)$$

where we now assume that a single mode $E_{in}(x,0)=V_i(0)e_i(x;r)$ is incident from the left. Performing cross-product in Eq.(6) with

$$\sum_m k_{zm,v}e_{jm}^{(v)}(x;r)\ \text{ for }\ k_{zm,v}=k_v+\frac{2m\pi}{\Lambda}$$

and integrating over the cross section (cs) of guiding structure, the modal voltages satisfying the field orthogonality condition of supermodes are found to be

$$V_1(0)=A_1V_i\quad ,\quad V_2(0)=A_2V_i\quad , \qquad (7)$$

where the input transformer coefficient A_v is given by

$$A_{\nu}=\frac{1}{C_{\nu}}\int_{cs}\left\{e_{i}(r)\sum_{m}k_{zm,\nu}e_{jm}^{(\nu)}(x;r)\right\}\,ds$$

with the appropriate normalization constant C_{ν} determined by the field orthogonality condition

$$\int_{cs}\left\{\sum_{m}k_{zm,s}e_{jm}^{(s)}(x;r)\sum_{n}e_{jn}^{(\nu)}(x;r)\right\}\,ds=C_{\nu}\delta_{s\nu} \quad (8)$$

of multilayered periodic guiding structures which is derived for the first time by Ho.

The orthogonal supermodes generated at the input interface ($z=0$) propagate along the longitudinal z-direction, and the modal voltages V_{ν} at an arbitrary accessible terminal $z=z_o$ decay exponentially in terms of the leakage losses α_{ν}. However, if the sign of α_{ν} changes from positive to negative, the modal functions grow exponentially along with the optical coupler and are transmitted through the upper or lower channel. Then, the boundary conditions at an arbitrary output terminal z_o yield the following relations between transmission-line modal functions

$$V_{out}(z_o)e_{out}(r)\cong V_{1}e^{ik_{1}z_{o}}\sum_{n}e_{jn}^{(1)}(x;r)e^{i(2n\pi/\Lambda)z_{o}} + V_{2}e^{ik_{2}z_{o}}\sum_{n}e_{jn}^{(2)}(x;r)e^{i(2n\pi/\Lambda)z_{o}} \quad (9)$$

Utilizing the power normalization of output modal fields

$$\int_{cs}e_{out}(r)h_{out}^{*}(r)\,ds=1\,,$$

the output modal voltage $V_{out}(z_o)$ of Eq. (9) becomes

$$V_{out}(z_o)=\left(A_{1}B_{1}e^{ik_{1}z_{o}}+A_{2}B_{2}e^{ik_{2}z_{o}}\right)\equiv T_{f}V_{in}(0) \quad , \quad (10)$$

where T_f represents the transformation factor between input and output modal voltages, and the output transformer coefficient B_{ν} becomes

$$B_{\nu}=\int_{cs}\left\{h_{out}^{*}(r)\sum_{n}e_{jn}^{(\nu)}(x;r)e^{i(2n\pi/\Lambda)z_{o}}\right\}\,ds\,.$$

The equivalent transmission-line network describing the above electromagnetic analysis of the grating-assisted directional coupler is given in Fig. 4. Thus, we can define a convenient formalism to analyze the power transfer of TE modes, which is called *coupling efficiency* η. The coupling efficiency η represents the ratio of the output power ($V_{out}I^{*}_{out}$) to the input power ($V_{in}I^{*}_{in}$), and is obtained from Eq.(10)

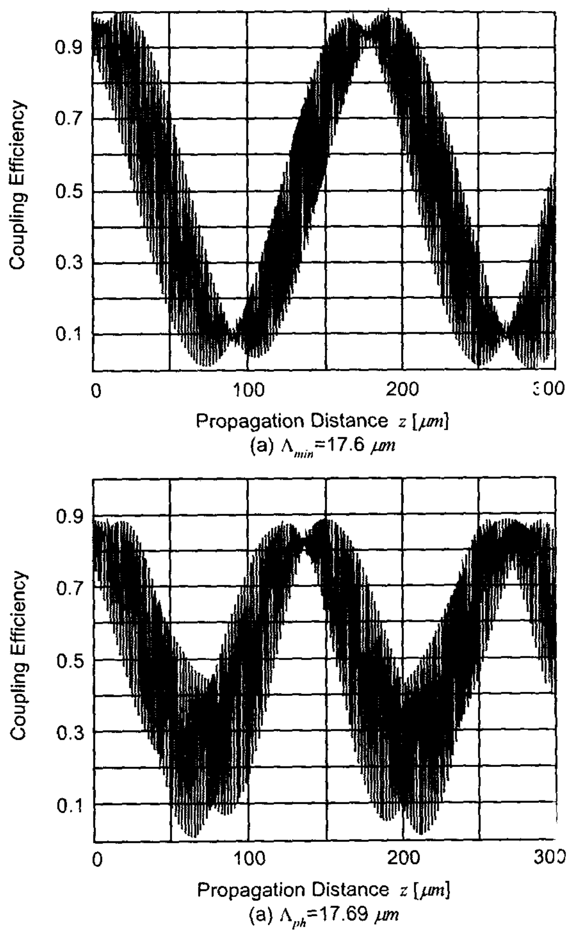

Fig. 5: Power transfer as a function of propagation distance z at (a) the minimum gap (resonance) condition and (b) the phase-matching condition.

$$\eta=\frac{P_{out}}{P_{in}}=\frac{\mathrm{Re}(k_{out})}{\mathrm{Re}(k_{in})}\left|T_{f}\right|^{2}\,. \quad (11)$$

To search the condition for maximum power transfer between two guiding channels of GAFC, we explore the coupling efficiency η as a function of the propagation distance z under the phase-matching Λ_{ph} and the resonance condition Λ_{min}. As shown in Fig. 5, no full power transfer between two grating-coupled guides always yields at the phase-matching condition Λ_{ph} representing the intersection point in Fig. 3, while the power transfer is almost over 90% with a coupling length of ~177 μm if a grating period Λ_{min} is chosen.

Finally, we evaluate the filtering properties of GAFC at the minimum-gap condition Λ_{min}=17.6 μm and the

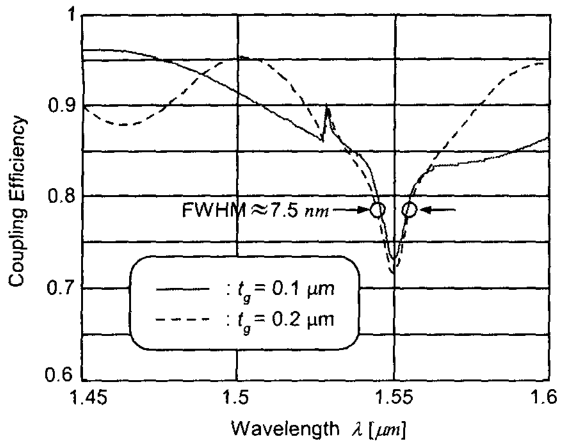

Fig. 6: Filtering characteristics of grating-assisted fiber coupler (GAFC).

coupling length L_c=177 μm for maximum power transfer between two dissimilar waveguides (fiber and film with grating). Figure 6 shows that the full width half maximum (FWHM) bandwidth of the Bragg reflection response is approximately 7.5 nm at the operating wavelength $\lambda = 1.55\ \mu m$, which is greater than the fiber Bragg gratings (FBGs) consisted of a refractive index modulation photo-imprinted in the core of optical fibers with a periodic UV light pattern.

3. CONCLUSION

We have analyzed the filtering properties in GAFC by using modal transmission-line theory based on a rigorous solution of boundary-value problems. From the numerical analysis, we have found that a maximum power transfers through the single mode fiber at a coupling length of ~177 μm satisfying the narrowest gap condition Λ_{min}=17.6 μm, and the full width half maximum (FWHM) bandwidth at the coupling length is approximately 7.5 nm regardless of the thickness of grating. Furthermore, we have proposed the fabrication possibility of fiber Bragg grating using planar grating configuration applicable to a wavelength reference in optical communication systems.

Reference

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