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PAPER

Effects of Air Gaps on Butt-Joints between Isotropic and Anisotropic Planar Waveguides

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SUMMARY Power transmission properties are investigated for a butt-joint which contains an air gap between an isotropic planar waveguide and an anisotropic one whose optical axis is lying in the plane defined by the propagation axis and the normal of the waveguide surface. New transmission coefficients are introduced for estimating the optical-power which is launched out into the gap from the incoming waveguide. Wave propagation through the gap is analyzed on the basis of the *BPM* concept. And the power transmitted across the interface between the gap and the outgoing waveguide is evaluated by means of the overlap integral of the field profiles. The effects of the air gap and the refractive index of filling liquid as well as axial displacement and angular misalignment are discussed on the basis of numerical results.

key words: *butt-joint, anisotropic waveguide, air gap, beam propagation method, transmission coefficient*

1. Introduction

Improvement of power-coupling efficiency between two different waveguides has been of major interest in light transmission optics. Butt-joining is a simple method widely used to interconnect waveguides. Many interesting papers have been reported on a wide variety of butt-joints up to now: optical fiber splices [1]-[3], excitation of optical fibers or devices by light sources [4], [5], and butt-joints between optical fibers and devices [6], [7]. However, most of them have concerned isotropic cases and there have been few studies on junctions involving anisotropic waveguides.

We have already reported studies on butt-joints between an isotropic single-mode planar waveguide and an anisotropic one consisting of uniaxial material in which the optical axis lies in the plane defined by the propagation axis and the normal of the waveguide surface [8], [9]. In general, angular misalignment between the waveguides may bring about a wedge-shaped air gap at the end-to-end junction. However, the influence of the air gap has not been taken into consideration in our previous studies. In the present paper, we investigate the effects of the air gap on the optical power transmitted across the butt-joint [10]. Wave propagation in the gap is analyzed on the basis of the *BPM* concept [11]. Coupling efficiency at the interface between the gap and the outgoing waveguide is evaluated by means of the overlap integral of the field profiles [9].

2. Waveguide Structure

A symmetric isotropic planar waveguide with a thickness d_1 is connected to a symmetric anisotropic one with a thickness d_2 through an air gap as shown in Fig. 1, together with coordinate systems used for the analysis. It is assumed that both incoming and outgoing waveguides support only the dominant mode. Optical waves are propagated along the z' axis in the incoming waveguide and along the z axis in the outgoing waveguide. The displacement of the waveguide axes and the gap width measured at $x'=0$ are represented by $\Delta x'$ and $\Delta z'$, respectively, and θ is the misalignment angle, in the x-z plane, between the waveguide axes. The subscripts 1, 2, and g refer to the quantities belonging to the incoming waveguide, the outgoing one, and the air gap, respectively. ε_{1p} and $\hat{\varepsilon}_{2p}$ whose additional subscript p represents f (film) or s (substrate) are scalar and tensor permittivities, respectively. The air gap may be filled with an index-matching liquid with a refractive index n_g.

Assume the optical axes in both the film and substrate of the outgoing waveguide are contained in the x-z plane and are parallel to each other. The permittivity tensor in the waveguide coordinate system is then expressed as

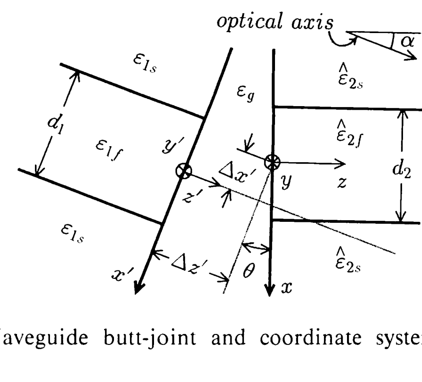

Fig. 1 Waveguide butt-joint and coordinate systems for the analysis.

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$$\hat{\varepsilon}_{2p}=\begin{bmatrix}\varepsilon_{xxp} & 0 & \varepsilon_{xzp}\\ 0 & \varepsilon_{yyp} & 0\\ \varepsilon_{xzp} & 0 & \varepsilon_{zzp}\end{bmatrix} \tag{1}$$

where

$$\begin{aligned}\varepsilon_{xxp}&=\varepsilon_0(n_{op}^2\cos^2\alpha+n_{ep}^2\sin^2\alpha)\\ \varepsilon_{xzp}&=\varepsilon_0(n_{ep}^2-n_{op}^2)\cos\alpha\sin\alpha\\ \varepsilon_{zzp}&=\varepsilon_0(n_{op}^2\sin^2\alpha+n_{ep}^2\cos^2\alpha)\\ \varepsilon_{yyp}&=\varepsilon_0 n_{op}^2\end{aligned} \tag{2}$$

In the above equations, n_{op} and n_{ep} are the refractive indices for the ordinary and extraordinary rays, respectively, and α is an angle between the z axis and the optical axis, which is called the oblique angle. We have the relation $n=\sqrt{\varepsilon/\varepsilon_0}$ between refractive indices and permittivities, where ε_0 is the free-space permittivity.

3. Analytical Method

With some appropriate modification we can apply the analytical method described in [9] to the present case. It is essentially a three-point problem. The first is how to treat transmission across the boundary between the incoming isotropic waveguide and the air gap. The second is propagation through the air gap. And the third is estimation of the power coupling between the air gap and the outgoing anisotropic waveguide.

The first point is just a transmission and reflection problem of the plane wave at the plane boundary. Eigenmodes in the slab waveguide can be decomposed into plane waves with evanecent tails outside the film which, bouncing back and forth between the film surfaces, propagate along the waveguide with the proper phase constant. On the other hand, the incoming waveguide is considered to be terminated normally by a dielectric material with a refractive index n_g. In this situation, the plane waves in the incoming waveguide are reflected at the boundary, satisfying the Snell's reflection law. This means that the reflected plane waves form exactly the same profile as the incident waves. In order to satisfy the boundary condition at $z=0$ plane, the transmitted waves should also form the identical profile. Consequently, the field profile just behind the interface should be exactly analogous to the eigenmode profile in the incoming waveguide, reducing its power to

$$t_1=\begin{cases}\dfrac{4N_1\sqrt{n_g^2-n_{1f}^2+N_1^2}}{(N_1+\sqrt{n_g^2-n_{1f}^2+N_1^2})^2} & \text{TE mode}\\[2ex] \dfrac{4N_1\sqrt{n_g^2-n_{1f}^2+N_1^2}}{\left(\dfrac{n_gN_1}{n_{1f}}+\dfrac{n_{1f}}{n_g}\sqrt{n_g^2-n_{1f}^2+N_1^2}\right)^2} & \text{TM mode}\end{cases} \tag{3}$$

where $N_1=\beta_1/k_0$, the effective refractive index so called.

A free space may be regarded as a limiting case of a weakly guiding structure. Therefore, the basic *BPM* concept is applicable to free-space propagation if an initial field distribution is given. The slowly varying complex amplitude of the optical wave is formally expressed as[11]

$$W(x',z'+\Delta z')=\exp\left\{-j\Delta z'\frac{\nabla_t^2}{\sqrt{\nabla_t^2+k_0^2n_g^2}+k_0n_g}\right\}W(x',z'). \tag{4}$$

Numerical calculations by means of (4) together with the initial field distribution $W(x',0)$ present the field intensity at any discrete point on the x axis. Thus, the incident field to the outgoing waveguide can be obtained numerically for an arbitrary misalignment angle.

Once, the field distribution on either side of the interface is given, whether an anisotropic waveguide is involved or not, we can estimate power-coupling coefficients accurately by means of the overlap integral between the field profiles [9]

$$T=t_2\cdot\frac{\left|\int F_g\cdot F_2^*dx\right|^2}{\int|F_g|^2dx\cdot\int|F_2|^2dx} \tag{5}$$

where

$$t_2=\begin{cases}\dfrac{4n_g\cos\theta\sqrt{N_2^2-n_g^2\sin^2\theta}}{(n_g\cos\theta+\sqrt{N_2^2-n_g^2\sin^2\theta})^2} & \text{TE mode}\\[2ex] \dfrac{4n_g\cos\theta\sqrt{N_2^2-n_g^2\sin^2\theta}}{\left(N_2\cos\theta+\dfrac{n_g}{N_2}\sqrt{N_2^2-n_g^2\sin^2\theta}\right)^2} & \text{TM mode}\end{cases} \tag{6}$$

The function F in (5) represents the y component of the electric field for the TE mode and that of the magnetic field for the TM mode, and $N_2=\beta_2/k_0$ in (6). Therefore, the optical power transmitted through the whole region can be estimated by means of (5) multiplied by t_1.

4. Numerical Results

The refractive indices of the incoming waveguide are chosen so that $n_{1s}=1.51$ and $n_{1f}=1.5115$, which are typical values for optical fibers in practical use. The outgoing waveguide is assumed to be consisting of $LiNbO_3$; so the refractive indices are chosen as $n_{os}=2.272$, $n_{of}=2.274$, $n_{es}=2.187$, and $n_{ef}=2.189$. It is also assumed that $d_1=d_2=6\lambda_0$, where λ_0 is the free-space wavelength.

In order to achieve high coupling efficiency, we will investigate first how to choose the refractive index of filling liquid. Figure 2 illustrates the power-coupling coefficients for the TM mode as a function of the refractive index n_g of the gap when $\Delta z'/\lambda_0 = 10$, $\Delta x' = 0$, $\theta = 0°$, and $\alpha = 0°$. It is understood from the figure that the optimum value of n_g which offers the maximum coupling efficiency is about 1.85 and that about a 16% improvement in coupling efficiency can be achieved. It is also understood that the power-coupling coefficients are almost constant over a wide range of n_g, keeping values close to the maximum.

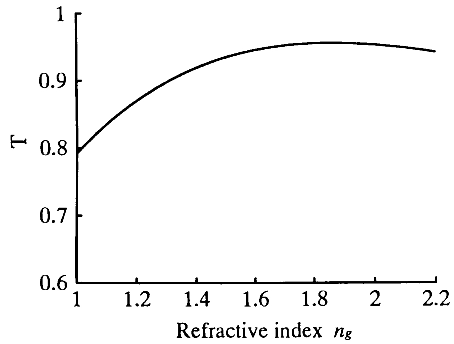

Fig. 2 Power-coupling coefficients for the TM mode as a function of refractive index n_g of the gap, where $\Delta z'/\lambda_0 = 10$, $\Delta x'/\lambda_0 = 0$, and $\alpha = 0°$.

Next, Fig. 3 shows the power-coupling coefficients for the TM mode as a function of the normalized displacement $\Delta x'/\lambda_0$ with the oblique angle α as a parameter. It is assumed in these cases that there is no angular misalignment between the waveguide axes. The normalized distance of the gap is chosen as (a) $\Delta z'/\lambda_0 = 10$ and (b) $\Delta z'/\lambda_0 = 50$. The solid lines in the figure represent the results for the case where the gap is filled with an index-matching liquid with a refractive index $n_g = 1.8$. The dashed lines show the results for the case of the air gap, that is $n_g = 1.0$. The dashed and dotted lines in Fig. 3(a) correspond to the results for the butt-joint without the gap [8], [9]. In general, the wider the gap, the worse the coupling efficiency. This effect is much more serious against the air gap. On the other hand, an appropriate filling liquid can compensate the influence of the gap almost completely. Indeed, a narrow gap filled with an appropriate liquid offers a little bit better coupling efficiency than the direct contact of waveguides.

Lastly, the effects of the angular misalignment on the power-coupling coefficients are shown in Fig. 4 with the oblique angle and displacement of the

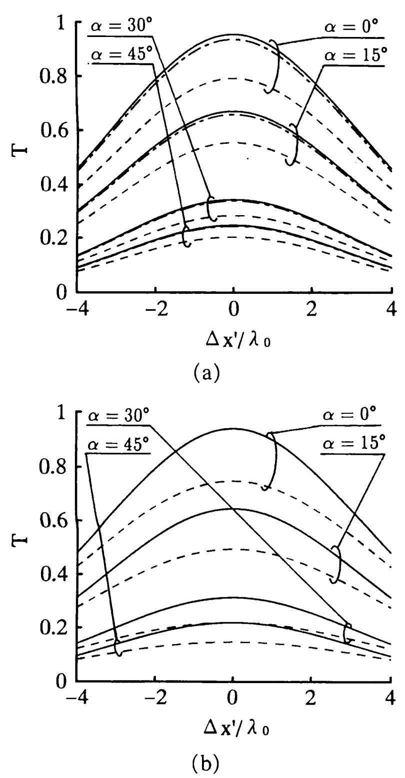

Fig. 3 Power-coupling coefficient versus normalized displacement $\Delta x'/\lambda_0$ with oblique angle as a parameter. The solid lines and dashed lines show the results for the cases of $n_g = 1.8$ and $n_g = 1.0$, respectively. The dashed and solid lines in (a) illustrate those butt-joints without the gap [9]. The normalized distance of the gap is chosen as (a) $\Delta z'/\lambda_0 = 10$ and (b) $\Delta z'/\lambda_0 = 50$.

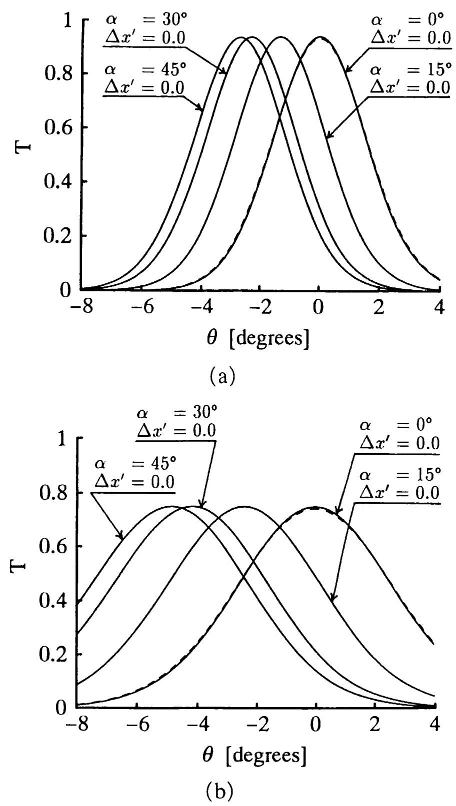

Fig. 4 Power-coupling coefficient versus misalignment angle for the case of $\Delta z'/\lambda_0 = 50$ with oblique angle and the normalized displacement as parameters. The dashed lines illustrate the results for the TE mode. The refractive index of the gap is chosen as (a) $n_g = 1.8$ and (b) $n_g = 1.0$.

waveguide axes as parameters. The normalized distance of the gap is chosen as $\Delta z'/\lambda_0=50$ in this case and the refractive index of the gap is assumed to be (a) $n_g=1.8$ and (b) $n_g=1.0$. Although the values of $\Delta x'/\lambda_0$ in the figure are so optimally adjusted that the peak value of each curve becomes maximum, all of them are nearly equal to zero. The dashed lines represent the results for the TE mode. We can recognize stronger θ dependence of the characteristics in Fig. 4 (a) than in Fig. 4(b), which suggests that the filling liquid suppresses the field profile to broaden in the gap region. We can also recognize significant α dependence of the characteristics only for the TM mode. Their θ dependence is analogous for both TE and TM modes. It may be possible to utilize these characteristics for polarization depending devices.

5. Conclusions

The power-coupling efficiency is analyzed for a butt-joint including an air gap between an isotropic planar waveguide and an anisotropic one consisting of uniaxial material with the optical axis being in the plane defined by the propagation axis and the normal of the waveguide surface. Transmission coefficients are introduced in order to estimate the waves which are launched out into the gap region from the incoming waveguide. Wave propagation through the gap is analized on the basis of the *BPM* concept. And the optical power coupled into the outgoing waveguide is evaluated by means of the overlap integral of the field profiles. Numerical data for some wide gaps are presented for various values of the oblique angle, the angular misalignment and displacement of the waveguide axes. The effects of the filling liquid are also investigated numerically.

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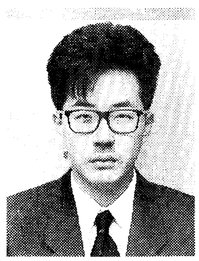

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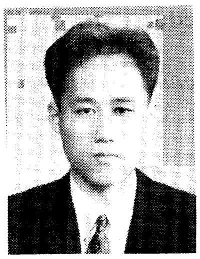

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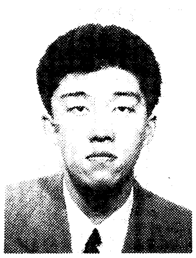

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