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# APPLICATION OF BEAM PROPAGATION METHOD TO PLANAR WAVEGUIDE BUTT–JOINTS

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## 1. Introduction

The beam propagation method(BPM) proposed by Feit and Fleck[1] has been successfully applied to the analysis of a wide variety of weakly guiding dielectric waveguides: optical fibers, planar waveguides, channel waveguides, and so on. Since reflected waves are not taken into account in the original BPM algorithm, some appropriate modification should be made when a significant amount of reflection can be expected[2],[3].

In the present paper, we propose two methods for simple modification to the BPM in characterizing waveguide butt-joints in which the refractive index difference between the waveguides interconnected is fairly large. The modification in both methods essentially relates to the Fresnel reflection. One is dealt with in the space domain and the other is done in the spectral domain. A comparison of the numerical results with those of another well-established method[4] shows that the present modification does work effectively.

## 2. Analytical Method

An incoming symmetric planar waveguide of thickness $d_1$ is butt-jointed to an outgoing one of thickness $d_2$ as shown in Fig. 1 where $\Delta s$ represents the axial displacement.

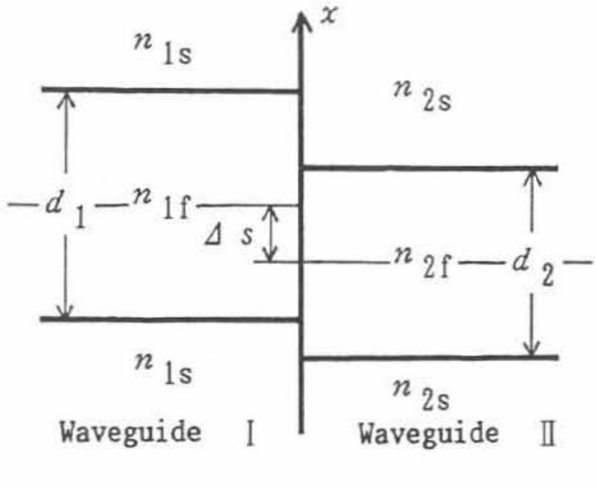


Fig. 1 Butt-joint between symmetric planar waveguides.

The refractive index difference $(n_{2f} - n_{1f})$ or $(n_{2s} - n_{1s})$ at the joint may be considerably large. It is assumed that both waveguides support only the dominant mode and the weakly guiding condition is satisfied, that is, $(n_{if} - n_{is})/n_{is} \ll 1$, $i = 1$ *or* 2. Then the original BPM analysis is accurately applicable to each waveguide. Therefore, if effects of the Fresnel reflection at the junction are estimated reasonably, the behavior of optical waves transmitted through the structure can be analyzed correctly on the basis of the BPM concept. We concentrate our discussion on the $TE$ mode in the following.

## 2.1 Method I

The optical wave in the incoming waveguide is traced up to the junction by means of the BPM. The field distribution obtained there is the modal field of the dominant mode in this waveguide. Since $(n_{2f} - n_{2s})/n_{2s} \ll 1$ the field profile just behind the junction would not be deformed and may be obtained by multiplying the transmission coefficient

$$t = \frac{2\sqrt{N_1 N_2}}{N_1 + N_2} \quad . \tag{1}$$

$N_1$ and $N_2$ in the above equation are defined as

$$N_1^2 = \frac{\int (n_{1p}E_1)^2 dx}{\int E_1^2 dx} \quad , \quad N_2^2 = \frac{\int (n_{2p}E_1)^2 dx}{\int E_1^2 dx} \, , \tag{2}$$

where $p = f$ *or* $s$ and $E_1$ is the transverse component of the electric field in the incoming waveguide. The optical wave in the outgoing waveguide after the junction can be traced again with the BPM starting from the resultant field. It would be rather logical to use the so-called effective refractive indices $\beta_1/k_0$ and $\beta_2/k_0$ in place of $N_1$ and $N_2$ in Eq. (1), respectively. However, this substitution, if used in the reflection coefficient, would lead to unreasonable results for waveguide discontinuities[5]. On the contrary, the definition of Eq. (2) offers legitimate results for the same problem[6].

## 2.2 Method II

The basic concept of the BPM algorithm is the plane-wave expansion of the modal field by means of the Fourier transformation. By virtue of the weakly guiding condition, each plane-wave component would propagate through the boundary with the transmission coefficient

$$t'^2 = \frac{4n_{1s}\cos\alpha\sqrt{n_{2s}^2 - n_{1s}^2\sin^2\alpha}}{\left(n_{1s}\cos\alpha + \sqrt{n_{2s}^2 - n_{1s}^2\sin^2\alpha}\right)^2} \quad , \tag{3}$$

where $\alpha$ is the incident angle of each plane wave. The effects of refraction would be negligible for the weakly guiding case, since the dominant components of the plane waves constructing the modal field are incident almost normally on the boundary. Therefore, multiplying the amplitude of each plane wave component in the incoming waveguide by $t'$ and converting the propagation constant of the plane waves into $n_{2s}k_0$, we can estimate the wave propagation anywhere in the outgoing waveguide.

These two methods are expected to give correct results concerning the transmitted waves and can be easily extended to treat a butt-joint in which an air gap exists at the joint between waveguides.

## 3. Numerical Results

The present methods are verified numerically in the following. The waveguide parameters are chosen so that $n_{1s} = 1.0$, $n_{1f} = 1.01$, $n_{2s} = 1.99$, $n_{2f} = 2.0$, $d_1 = 3\lambda$, and $d_2 = 2\lambda$ where $\lambda$ is a free-space wavelength. Fig. 2 shows the power-coupling efficiency estimated by the present methods. The ordinate is the output power normalized with the input power. The abscissa represents the normalized displacement $2\Delta s/(d_1 + d_2)$ between the waveguides. Numerical results obtained from

$$T_{ovp} = \frac{4\beta_1\beta_2}{(\beta_1+\beta_2)^2} \cdot \frac{\{\int E_1 \cdot E_2\, dx\}^2}{\int |E_1|^2 dx \cdot \int |E_2|^2 dx} \tag{4}$$

are also shown by the solid line in the figure for the sake of comparison. It is well-known that this formula has been applied accurately to the evaluation of transmitted powers[4],[6]-[8]. The results obtained by the Method I and II are in good agreement and the difference from the solid line is 2% at most in which computational errors in the numerical integration might be contained. Fig. 3 shows the results obtained from the original BPM without the Fresnel reflection taken into account. The maximum discrepancy is more than 10%.

## 4. Conclusions

Two methods of modification to the BPM are presented for the application of it to the analysis of discontinuities in weakly guiding waveguides. The modification is essentially based on the Fresnel reflection. One is introduced in the space domain and the other in the spectral domain. It is verified numerically that both methods present fairly good results. They can be easily extended to the case where an air gap exists between interconnected waveguides.

## References


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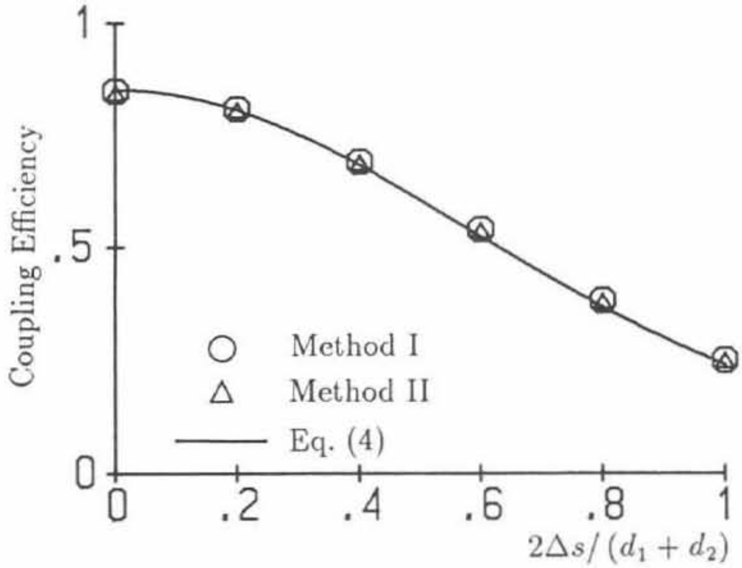


Fig. 2 Coupling efficiency versus axial displacement evaluated with the proposed methods.

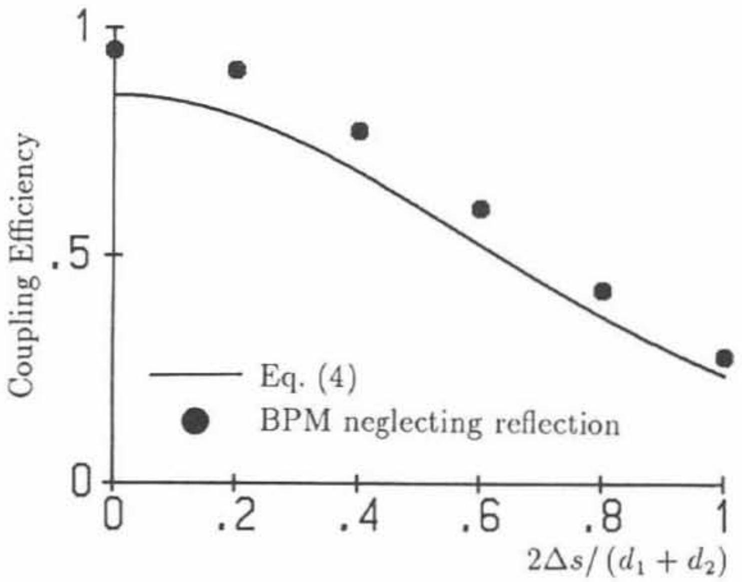


Fig. 3 Coupling efficiency versus axial displacement estimated by the original BPM without modification.