

# Analysis of a Polarization Splitter With a Multilayer Filter Using a Pade-Operator-Based Power-Conserving Fourth-Order Accurate Beam-Propagation Method

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(出版者 / Publisher)

IEEE

(雑誌名 / Journal or Publication Title)

IEEE Photonics Technology Letters / IEEE Photonics Technology Letters

(開始ページ / Start Page)

1858

(終了ページ / End Page)

1860

(発行年 / Year)

2006-09-01



After expressing the field as  $\mathcal{H}_y = H(x, z)\exp(-jk_0 n_0 z)$ , where  $n_0$  is the reference refractive index, we obtain

$$n^2 \frac{\partial}{\partial z} \left[ \frac{1}{n^2} \left( jk_0 n_0 H - \frac{\partial H}{\partial z} \right) \right] + jk_0 n_0 \frac{\partial H}{\partial z} = n^2 \frac{\partial}{\partial x} \left( \frac{1}{n^2} \frac{\partial H}{\partial x} \right) + k_0^2 (n^2 - n_0^2) H. \quad (3)$$

Equation (3) can be transformed into

$$\left[ -\frac{\partial}{\partial z} - n^2 \left( \frac{\partial}{\partial z} \frac{1}{n^2} \right) + 2jk_0 n_0 \right] \frac{\partial H}{\partial z} = PH \quad (4)$$

where

$$P = n^2 \frac{\partial}{\partial x} \left( \frac{1}{n^2} \frac{\partial}{\partial x} \right) + k_0^2 (n^2 - n_0^2) - jk_0 n_0 n^2 \left( \frac{\partial}{\partial z} \frac{1}{n^2} \right). \quad (5)$$

By analogy with the derivation of the Padé-operator-based BPM for the TE wave, we finally obtain the following (1,1) Padé expression for the TM wave:

$$\frac{\partial H}{\partial z} = -\frac{\frac{jP}{2k_0 n_0}}{1 + \frac{P}{4k_0^2 n_0^2}} H. \quad (6)$$

Note that the last term in (5) has often been neglected [4]. In this letter, this term is evaluated using [5, eq. (11)]. Auxiliary calculation shows that the inclusion of the second term in the left-hand side of (4) does not necessarily lead to reasonable results.

To evaluate the second derivative with respect to the transverse direction, we employ the fourth-order FD scheme [9], which takes into account the boundary condition at the dielectric interface.

The reference refractive index is updated as the field propagates [1]

$$n_0^2 = \frac{\int \left( k_0^2 |H|^2 - \frac{1}{n^2} \left| \frac{\partial H}{\partial x} \right|^2 \right) dx}{k_0^2 \int \left( \frac{|H|^2}{n^2} \right) dx}. \quad (7)$$

Based on the Poynting vector, the exact power can be expressed as [7]

$$P_{\text{TM}} = \frac{1}{2\omega\epsilon_0} \text{Re} \int \left( k_0 n_0 \frac{|H|^2}{n^2} + j \frac{H^*}{n^2} \frac{\partial H}{\partial z} \right) dx \quad (8)$$

in which  $\epsilon_0$  and  $\omega$  are the free-space permittivity and the angular frequency, respectively. For the TE wave, we also use the equations corresponding to (7) [1] and (8) [7].

It is interesting to note that the second term in (8) can be neglected, provided the slowly varying envelope approximation is maintained. This fact suggests that the second term should be included for the case where the variation of the field cannot be negligible in the propagation direction, such as in the filter region.

### III. ANALYSIS OF POLARIZATION SPLITTER

Fig. 1 shows the configuration to be considered here. We excite the field of either TE or TM mode from Waveguide #1, and intend to extract the TM wave in Waveguide #2 and the TE wave

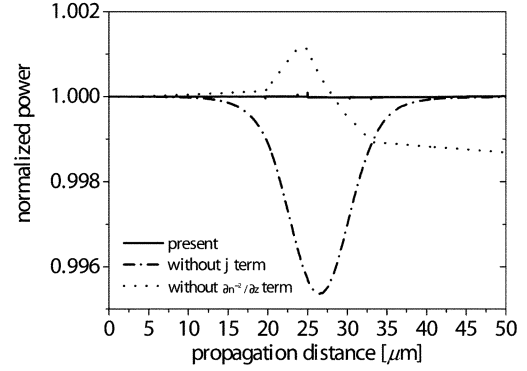


Fig. 2. Normalized power of the TM wave as a function of propagation distance ( $n_0$  is updated using (7),  $\lambda = 1.55 \mu\text{m}$ ).

in Waveguide #3 over a wide range of wavelengths. The refractive indexes of the core and cladding are taken to be  $n_{\text{co}} = 1.536$  and  $n_{\text{cl}} = 1.532$ , respectively. The normalized frequency of the waveguide is almost equal to  $V = 1.5$  at  $1.31 \mu\text{m}$ . The number of layers is taken to be 12. The thicknesses of the layers are determined by  $t_H$  (or  $t_L$ ) =  $\lambda_S / (4n_H$  (or  $n_L$ )  $\cos \theta$ ), where  $n_H$  and  $n_L$  are the refractive indexes in the high- and low-index layers, respectively. In this analysis  $\lambda_S$  is chosen to be  $1.11 \mu\text{m}$ . The transverse and longitudinal sampling widths are taken to be  $\Delta x = t_H/9$  and  $\Delta z = \Delta x \tan \theta$ , respectively.

Assuming that the incident field is regarded as a plane wave, the Brewster condition is satisfied when the angle of incidence is such that [10]

$$\sin^2 \theta = \frac{n_H^2 n_L^2}{n_{\text{co}}^2 (n_H^2 + n_L^2)}. \quad (9)$$

In the present case ( $n_H = 2.25$  and  $n_L = 1.45$ ),  $\theta$  is calculated to be  $52.5^\circ$ . It should be noted that the appropriate angle of incidence is not sensitive to wavelength change, leading to wideband characteristics of filtering properties.

The effective reflection distance designated as  $d_R$  should be chosen to maximize the reflectivity for the TE wave. Preliminary calculation at  $1.31 \mu\text{m}$  shows that the maximum reflectivity is obtained at  $d_R = t_H + t_L$ .

Before investigating polarization splitting behavior in detail, we first assess the effectiveness of the present method for evaluating the power. We calculate the normalized power as a function of propagation distance, in which  $n_0$  is updated using (7). The results for the TM wave are shown in Fig. 2, in which the data obtained without the  $\partial n^{-2}/\partial z$  term in (5) are shown for comparison. It is observed that the inclusion of the  $\partial n^{-2}/\partial z$  term contributes to power conservation. Fig. 2 also shows that negligence of the second ( $j$ ) term in (8), corresponding to the simple squared norm, results in variation of the normalized power in the filter region. Further examination shows that the inclusion of the second ( $j$ ) term leads to insensitivity of the power to the change of  $n_0$  (see Fig. 3). Note also that the power with or without the second ( $j$ ) term approaches unity at  $z = 50 \mu\text{m}$  once  $n_0$  is updated using (7), as shown in Fig. 2.

Fig. 4 shows the reflectivity and transmissivity as a function of wavelength. To validate the use of the FD-BPM, we also present the results obtained with the FDTD method. Good agreement is found to exist between both results (since the FDTD method is based on the second-order FD scheme,  $\Delta x$

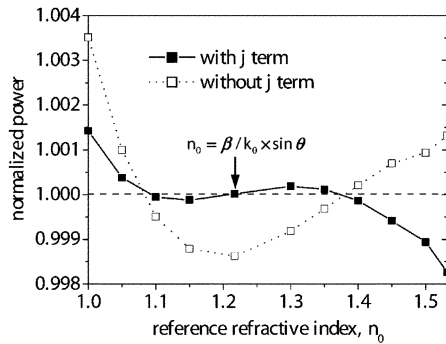


Fig. 3. Normalized power of the TM wave observed at  $z = 50 \mu\text{m}$  as a function of  $n_0$  (with  $\partial n^{-2}/\partial z$  term,  $\lambda = 1.55 \mu\text{m}$ ).

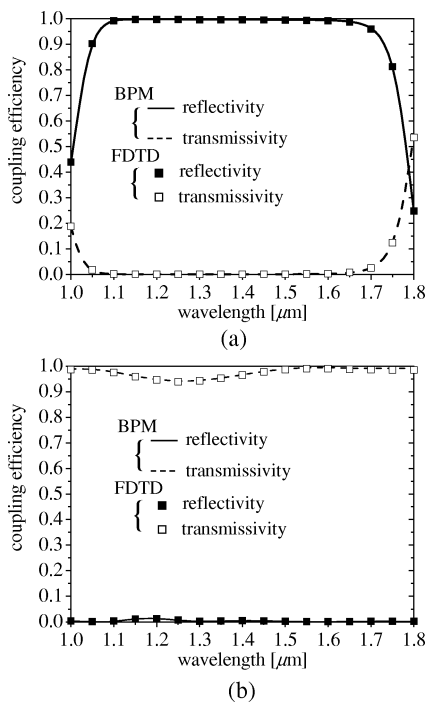


Fig. 4. Wavelength responses. (a) TE wave. (b) TM wave.

is chosen to be half that used in the FD-BPM to generate the comparable accuracy).

It is worth mentioning in Fig. 4 that a TM-pass/TE-reflection property is achieved over a wide range of wavelengths, which is not obtainable in the polarization splitters based on interference properties [15]. Reflectivities of more than 98% for the TE wave and transmissivities of more than 94% for the TM wave are obtained over a wavelength range of 1.1–1.65  $\mu\text{m}$ .

Fig. 5 shows the extinction ratios observed at the outputs of Waveguides #2 and #3. Over a wavelength range of 1.1–1.65  $\mu\text{m}$ , the extinction ratios are evaluated to be more than 21 dB in Waveguide #2 and 18 dB in Waveguide #3 (the use of Fresnel-operator-based power-conserving BPM causes a maximum error of about 3 dB).

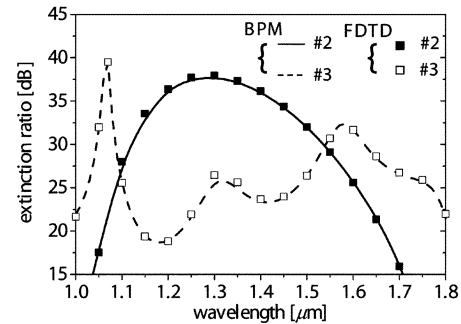


Fig. 5. Extinction ratios as a function of wavelength.

#### IV. CONCLUSION

A (1,1) Padé-operator-based FD-BPM with a power conserving property has been used to analyze a polarization splitter with a multilayer filter. As a result, reflectivities of more than 98% for the TE wave and transmissivities of more than 94% for the TM wave are obtained over a wide wavelength range of 1.1–1.65  $\mu\text{m}$ .

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