TM Waves Guided by Nonlinear Planar Waveguides

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Abstract —This paper presents a numerical method for calculating the dispersion relations and field distributions of stationary nonlinear TM waves guided by optical planar waveguides with intensity-dependent permittivities. The method can basically treat arbitrary linear permittivity profiles and arbitrary types of the nonlinearity, since it is based on a numerical integration of the nonlinear wave equation. In this paper, the numerical results for TM waves guided by a symmetric nonlinear film with linear claddings and a three-layer waveguide with a nonlinear cover have been presented for different mechanisms of the nonlinearity and compared with those for TE waves. The treated waveguide is weakly guiding and the nonlinearity is of the Kerr type. It is shown that under these assumptions, the dispersion relations for TM waves are similar to those for TE waves except for the power levels required for operation. The behavior of TM waves is also little affected by the nonlinear mechanism. These features can be derived from the fact that the longitudinal electric field component E_z is fairly small compared with the transverse component E_x.

I. Introduction

NONLINEAR WAVES in optical planar waveguides have recently received considerable attention in connection with applications to optical signal processing and integrated optics [1]–[4]. These waveguides consist of one or more nonlinear media characterized by intensity-dependent permittivities. The TE and TM waves can be supported in such nonlinear planar waveguides in the same way as in linear waveguides. Since the TE waves have only one electric field component, analytical solutions are available for many waveguide structures. To date, the dispersion relations for TE waves have been investigated for several waveguide structures including three-layer waveguides [1]–[9] and graded-index waveguides [10], [11], [23]. Moreover, the effects of non-Kerr-like nonlinearity on nonlinear waves [12], [13] and the stability of nonlinear waves [14] have been investigated. On the other hand, since the TM waves have two electric field components, i.e., longitudinal (E_z) and transverse (E_x) ones, the analysis is more complicated than that for TE modes. The dispersion relations for TM waves have been analyzed under many assumptions [15]–[17]. It has been pointed out that a uniaxial approximation based on the E_z^2 nonlinearity does not lead to physically useful results [18]. More recently, the exact dispersion relations for TM waves guided by a linear–nonlinear interface have been presented [19]–[21]. However, very little is known about the accurate behavior of nonlinear TM waves in optical planar waveguides with multiple interfaces, especially three-layer waveguides [22], which are important from the viewpoint of device applications.

This paper presents a numerical analysis of stationary nonlinear TM waves guided by optical planar waveguides. Maxwell's equations are solved numerically by using the Runge–Kutta method. This numerical integration method can be applied for every situation, including arbitrary profiles of the linear permittivity and arbitrary types of the nonlinearity. The usefulness and the versatility of the method have already been demonstrated for the nonlinear TE waves in several planar waveguides [23]. The dispersion relations for the TM waves guided by three-layer waveguides are solved numerically for every mechanism of the nonlinearity [19] and are compared with those for TE waves. The electric field distributions are also presented. A significant difference cannot be found between the dispersion relations for TM and TE waves except for the power levels required for operation.

II. Theory

We present a numerical method for calculating the dispersion relations for stationary nonlinear TM waves propagating with a constant mode index and transverse field distributions. The method can basically deal with general nonlinear planar waveguides. However, it requires that analytical solutions be available for the fields in semi-infinite outer layers. As an example, we consider here a three-layer waveguide with a Kerr-like nonlinear cover and describe the method briefly [23]. For the sake of the analysis, we introduce a hypothetical linear cover of the type shown in Fig. 1, where the nonlinearity is neglected and the fields decay exponentially in the $-x$ direction. The linear cover far from the guiding region does not bring a large error, since the power carried by stationary waves is confined to the vicinity of the film. A few comments will be made on this problem in the following section. The stationary nonlinear TM waves have three field components, and the vector fields can be expressed as

$$\begin{aligned} \boldsymbol{E}(\boldsymbol{r}, t) &= \{ E_x \boldsymbol{x} + jE_z \boldsymbol{z} \} \exp[j(\omega t - \beta k_0 z)] \\ \boldsymbol{H}(\boldsymbol{r}, t) &= H_y \boldsymbol{y} \exp[j(\omega t - \beta k_0 z)] \end{aligned} \tag{1}$$

where k_0 is the free-space wavenumber and β is the mode

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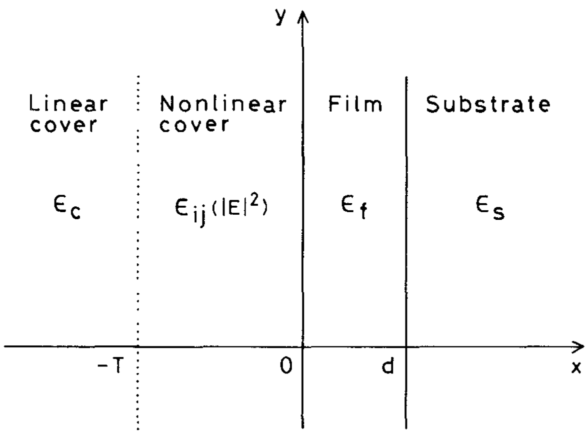


Fig 1. Cross section of the three-layer waveguide with a nonlinear cover A hypothetical linear cover ($x < -T$) is introduced in order to facilitate the analysis.

index. In (1), a specific phase relation among field components is taken into account so that E_x, E_z, and H_y are real-valued variables. The imaginary unit j indicates that the x and z components of the electric field are $\pi/2$ out of phase. Although Maxwell's equations for TM waves can be found in [19], we summarize them for the sake of completeness.

A. Treatment of Maxwell's Equations in the Nonlinear Cover

For TM waves, we obtain the following relations from Maxwell's equations by setting $H_z = 0$ and $\partial/\partial y = 0$:

$$H_y = \frac{1}{\beta}\sqrt{\frac{\epsilon_0}{\mu_0}}\,\epsilon_{xx}E_x \tag{2}$$

$$\frac{dH_y}{dx} = -k_0\sqrt{\frac{\epsilon_0}{\mu_0}}\,\epsilon_{zz}E_z \tag{3}$$

$$\frac{dE_z}{dx} + \beta k_0 E_x = k_0\sqrt{\frac{\mu_0}{\epsilon_0}}\,H_y \tag{4}$$

where

$$\epsilon_{xx} = \epsilon_c + \alpha\left(E_x^2 + \gamma E_z^2\right) \tag{5}$$

$$\epsilon_{zz} = \epsilon_c + \alpha\left(E_z^2 + \gamma E_x^2\right). \tag{6}$$

Here ϵ_0 and μ_0 are the permittivity and permeability of free space, respectively; ϵ_{xx} and ϵ_{zz} are elements of the diagonal permittivity tensor. The nonlinearity is assumed to be of the Kerr type. The quantity ϵ_c is the zero-field permittivity of the nonlinear cover and α is a nonlinear coefficient. The constant γ takes on different values depending on the mechanism of the nonlinearity [19]: $\gamma = 1$ for electrostriction and heating, $\gamma = 1/3$ for electronic distortion, and $\gamma = -1/2$ for molecular orientation. Substituting (2) into (3) and (4), we have a system of first-order differential equations for E_x and E_z.

To use the Runge–Kutta method as a numerical integration, the system must be rewritten in a normal form. After some mathematical manipulations, we have

$$\frac{dE_x}{dx} = -\beta k_0 E_z \times \frac{\epsilon_{zz} - 2\alpha\gamma\left(1 - \epsilon_{xx}/\beta^2\right)E_x^2}{\epsilon_{xx} + 2\alpha E_x^2} \tag{7}$$

$$\frac{dE_z}{dx} = \frac{k_0}{\beta}\left(\epsilon_{xx} - \beta^2\right)E_x. \tag{8}$$

For given interface field intensities $E_x(-T)$ and $E_z(-T)$, we can calculate the fields $E_x(x)$ and $E_z(x)$ at any position in the nonlinear cover by integrating (7) and (8) numerically. Then $H_y(x)$ is calculated from (2). Numerical solutions for $E_z(0)$ and $H_y(0)$ at the cover–film interface are used in the following boundary value problem.

B. Characteristic Equation

We here consider a procedure for obtaining the dispersion relations for TM waves. We first present the fields in linear regions:

$$H_y = \begin{cases} H_y(-T)\exp\left[\xi k_0(x+T)\right], & x < -T \\ H_y(0)\left\{\cos(\kappa k_0 x) + G\cdot\sin(\kappa k_0 x)\right\}, & 0 < x < d \\ H_y(0)\left\{\cos(\kappa k_0 d) + G\cdot\sin(\kappa k_0 d)\right\} & \\ \quad\cdot\exp\left[-\delta k_0(x-d)\right], & d < x \end{cases} \tag{9}$$

where

$$\xi^2 = \beta^2 - \epsilon_c \tag{10}$$

$$\kappa^2 = \epsilon_f - \beta^2 \tag{11}$$

$$\delta^2 = \beta^2 - \epsilon_s \tag{12}$$

$$G = -\frac{\epsilon_f\delta}{\epsilon_s\kappa} \times \frac{1 - \dfrac{\epsilon_s\kappa}{\epsilon_f\delta}\tan(\kappa k_0 d)}{1 + \dfrac{\epsilon_f\delta}{\epsilon_s\kappa}\tan(\kappa k_0 d)}. \tag{13}$$

Here $H_y(-T)$ and $H_y(0)$ are the magnetic field intensities at interfaces $x = -T$ and $x = 0$, respectively. In (9), the continuity of H_y and E_z at the film–substrate interface $x = d$ has already been considered and the z and time dependence has been dropped. If $\kappa^2 < 0$, the circular functions in (9) and (13) are replaced by the corresponding hyperbolic functions.

For an interface intensity $E_x(-T)$ given as a nonlinear parameter, we determine the mode index β so that the x-directed wave impedance E_z/H_y is continuous at both the interfaces $x = -T$ and $x = 0$. Once a trial value for the mode index is given, we can determine $H_y(-T)$ from the continuity of wave impedance at the interface $x = -T$:

$$\frac{E_z(-T)}{H_y(-T)} = -\frac{\xi}{\epsilon_c}\sqrt{\frac{\mu_0}{\epsilon_0}} \tag{14}$$

and subsequently $E_z(-T)$ from (2). For these initial values, $E_z(0)$ and $H_y(0)$ at the nonlinear cover–film interface are calculated by using the Runge–Kutta method. From the continuity condition of wave impedance at $x = 0$, we obtain the following characteristic equation:

$$\frac{E_z(0)}{H_y(0)} = -\frac{\kappa}{\epsilon_f}\sqrt{\frac{\mu_0}{\epsilon_0}}\cdot G. \tag{15}$$

In this paper, the root β of this equation is determined by using Newton's method. If the waveguide is symmetric, only one half of the waveguide cross section is considered. The mode index can be obtained by $E_z(x_0)=0$ for even modes and by $E_x(x_0)=0$ for odd modes, where x_0 is the coordinate of the waveguide axis. The existence of asymmetric modes can be generally expected because of an intensity-dependent permittivity effect even if the waveguide is symmetric. However, these modes can be regarded as modes in the asymmetric waveguide. Once the mode index is determined, we can easily calculate the total power flow by

$$P = \frac{1}{2}\int_{-\infty}^{\infty} E_x(x)H_y(x)\,dx. \tag{16}$$

Here the power flow in linear regions can be expressed analytically.

III. Numerical Results and Discussion

In this section, we present numerical results for the dispersion relations of two three-layer waveguides: one is the three-layer waveguide with a nonlinear cover shown in Fig. 1 and the other is the symmetric nonlinear film of thickness d bounded by two identical linear claddings of permittivity ϵ_c $(=\epsilon_s)$. In the latter case, the elements of the permittivity tensor of the nonlinear film are given by (5) and (6), where ϵ_c is replaced by ϵ_f. The mode index was computed to within the tolerance 10^{-9} for a given interface amplitude using the fourth-order Runge–Kutta method. The nonlinear region was divided into 2000 segments. All numerical results presented here were calculated for the following values: free-space wavelength $\lambda = 0.5145$ μm, film permittivity $\epsilon_f = 1.57^2 = 2.4649$, cover (or cladding) permittivity $\epsilon_c = 1.55^2 = 2.4025$, substrate permittivity $\epsilon_s(=\epsilon_c) = 2.4025$, and nonlinear coefficient $\alpha = 0.6377\times10^{-11}$ m^2/V^2. The refractive index difference between film and cover (or substrate) is 0.02 and hence the waveguide is weakly guiding. But this refractive index difference is fairly large for nonlinear device applications.

First, we present the results for the symmetric nonlinear film. Fig. 2 shows the total power flow for the first three TM_n modes $(n=0,1,2)$ as a function of the mode index for the film thickness $d = 2.0$ μm. The dispersion relations are calculated for three mechanisms of the nonlinearity $(\gamma = 1, 1/3, -1/2)$. For comparison, the results for TE modes are also shown in the figure. The nonlinearity for TE waves arises from the transverse field component E_y. In this example, the fundamental $(n=0)$ and first higher order $(n=1)$ modes can be supported even if the film is linear $(\alpha=0)$. These TM and TE modes are almost degenerate in the limit $\alpha = 0$ (or zero field), since the waveguide treated here is weakly guiding. The dispersion curves for second higher order $(n=2)$ modes have a double-valued

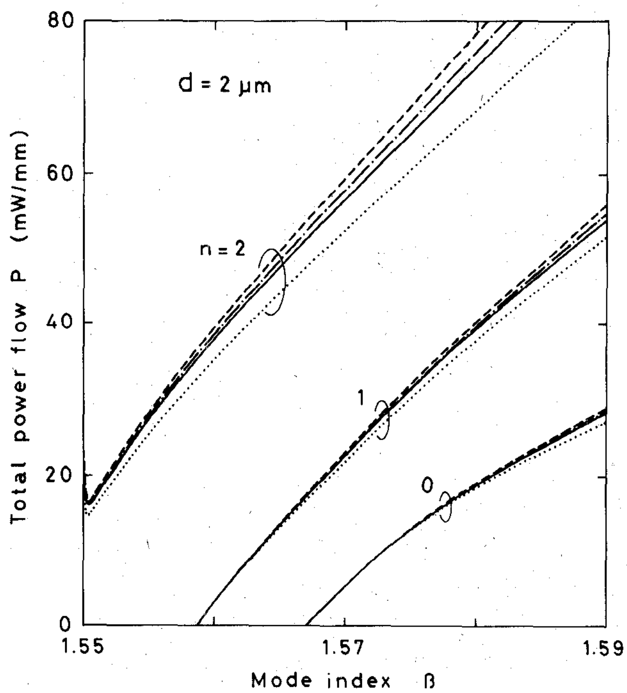


Fig. 2. Dependence of the total power flow P on the mode index β for the first three TM_n modes ($n = 0$, 1, and 2) guided by the nonlinear symmetric waveguide with linear claddings. The dispersion curves for TM_n modes are plotted for three mechanisms of the nonlinearity; $\gamma = 1$ (solid line), $1/3$ (dotted–dashed line), and $-1/2$ (dashed line), together with those for TE_n modes (dotted line).

behavior, because the power flow in the linear cladding diverges in the limit $\beta = \epsilon_c^{1/2}$. It is found that the power flow guided by the TM wave is always greater than that guided by the TE wave with the same value of β. For a given mode index, the power flow required for nonlinear TM waves also increases as the value of γ decreases. The reason is that for decreasing values of γ, the nonlinear effect becomes equivalently small and hence further power is required to achieve the same values of β. A similar situation takes place for nonlinear TE waves in saturable and non-Kerr-like nonlinear media [12], [13], [22], [23]. In contrast to these cases, the nonlinear TM waves are not strongly affected by the value of γ, as shown in Fig. 2. This means that E_x is the dominant field component and the nonlinearity for TM waves arises mainly from this component. Although this conclusion has already been pointed out [18], we calculate the electric field distributions $E_x(x)$ and $E_z(x)$ to confirm it numerically. Fig. 3 shows the distributions of TM_0 and TM_1 modes in the waveguide treated in Fig. 2 for three values of the mode index. Note that field distributions are drawn so that the maximum value of $E_x(x)$ becomes unity. Fig. 3 shows that the field ratio $E_{z\,\max}/E_{x\,\max}$ is not strongly influenced by the power flow, because the field-induced change in refractive index is of the order of 0.01 and the nonlinear waveguide can be still regarded as a weakly guiding waveguide. In our example, $|E_z(x)|^2_{\max}$ is approximately 100 times less than $|E_x(x)|^2_{\max}$. However, the field distributions depend strongly on the power flow. As the mode index increases, the fundamental TM_0 mode becomes a self-focusing wave

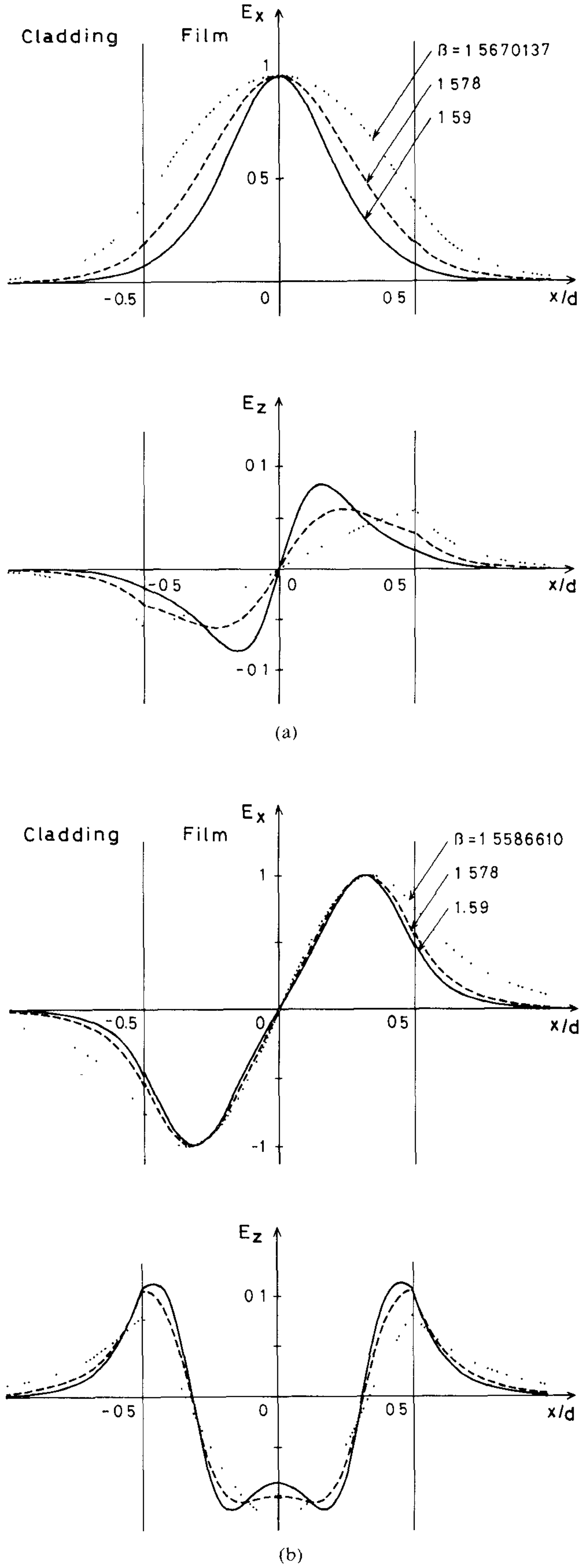


Fig. 3. Electric field distributions of the TM_0 and TM_1 modes in the nonlinear symmetric waveguide for $d = 2$ μm and $\gamma = -1/2$. (a) TM_0 mode. (b) TM_1 mode

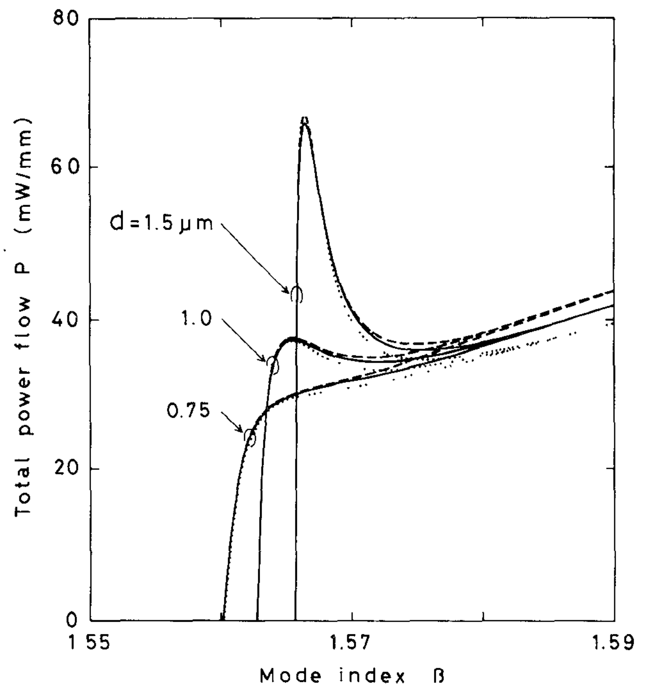


Fig. 4 Dependence of the total power flow P on the mode index β for the TM_0 mode guided by the three-layer waveguide with nonlinear cover for three film thicknesses d The dispersion curves are plotted for two nonlinear mechanisms; $\gamma = 1$ (solid line) and $-1/2$ (dashed line), together with those for TE_0 modes (dotted line).

in an infinite nonlinear medium, whose field H_y (or E_x) is approximately expressed by the hyperbolic function "sech." For the most part, the general features of nonlinear TM modes are similar to those of nonlinear TE modes except for the power levels required for operation.

Next, we present the results for the three-layer waveguide with a nonlinear cover. Fig. 4 shows the total power flow for the fundamental TM_0 mode as a function of the mode index for the three film thicknesses $d = 0.75$, 1.0, and 1.5 μm. Although the results for $\gamma = 1/3$ are not shown in the figure, the dispersion curve is located between two curves for $\gamma = 1$ and $-1/2$. The difference of the dispersion relations between TM_0 and TE_0 waves is very small at low power levels. Fig. 5 shows the electric field distributions $E_x(x)$ and $E_z(x)$ of the TM_0 mode for $d = 1.5$ μm. The field distributions are drawn for three values of β. The behavior of the TM_0 mode can be interpreted in the same way as for the TE_0 mode [3]. As the power flow increases, the field maximum shifts out of the film region into the cover because of the increase in refractive index, and the TM_0 mode becomes a surface polariton guided by a single interface between linear and nonlinear dielectrics [19]–[21]. The multivalued behavior in the mode index, that is, the local maximum in the power flow, appears for the film thickness over a certain critical value d_{min}. The critical thickness for the TM_0 mode is slightly larger than that for the TE_0 mode. In this example, the critical thickness d_{min} is 0.87, 0.84 μm and the minimum power flow required for pulling the field maximum into the nonlinear cover is 33.4, 31.8 mW/mm for the

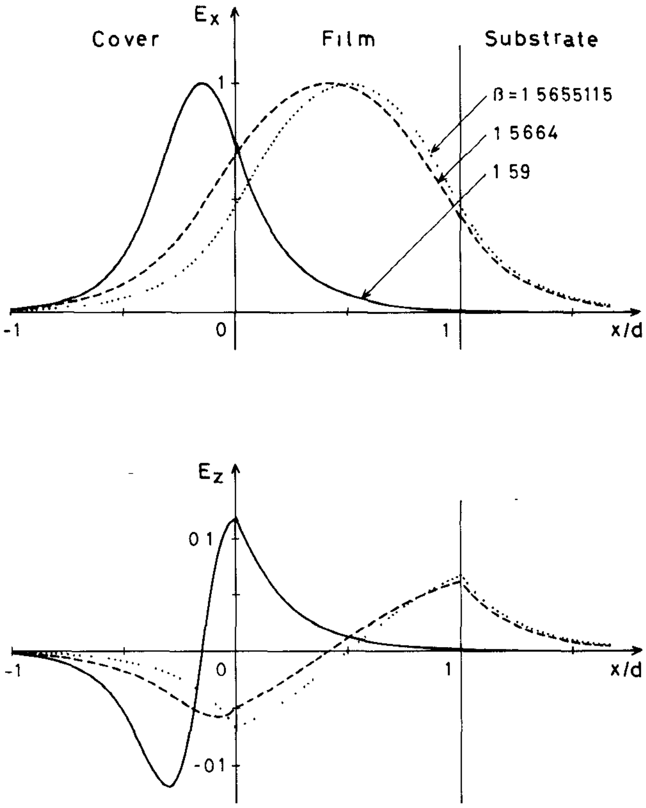


Fig. 5. Electric field distributions of the TM_0 mode in the three-layer waveguide with nonlinear cover for $d = 1.5$ μm and $\gamma = -1/2$. $\beta =$ 1.5655115, 1.5664, and 1.59 correspond to $P = 0.0$, 66.7 (maximum power), and 44.0 mW/mm, respectively.

TM_0 mode with $\gamma = -1/2$ and the TE_0 mode, respectively.

Fig. 6 shows the total power flow for the TM_1 mode as a function of the mode index for the two film thicknesses $d = 1.5$ and 2.0 μm. The mode index is always smaller than the refractive index of the linear film, and the peak appears in the power flow. Fig. 7 shows the electric field distributions of the TM_1 mode for $d = 1.5$ μm. The TM_1 mode has two field maxima in the film in the linear (or zero-field) case. One field maximum moves toward and into the nonlinear cover as the mode index increases, but the other remains in the film. Moreover, the field ratio $E_{z\max}/E_{x\max}$ unexpectedly decreases with increasing mode index. Therefore, the dispersion relations for the TM_1 mode are quite close to those for the TE_1 mode compared with previous examples, as shown in Fig. 6. In general, the behavior of higher order TM_n modes ($n \geqslant 2$) is similar to that of the TM_1 mode.

Finally, the only approximation used in the above calculation of the three-layer waveguide with a nonlinear cover is the introduction of the hypothetical linear cover. Since the maximum of the field moves within the nonlinear cover with guided power, the hypothetical boundary should be placed so as to make the influence of the linear cover on the dispersion relations negligible. In our calculation, the hypothetical boundary was located at $x = -3.0 \sim -5.0$ μm. Fortunately, it is seen from Figs. 5 and 7 that

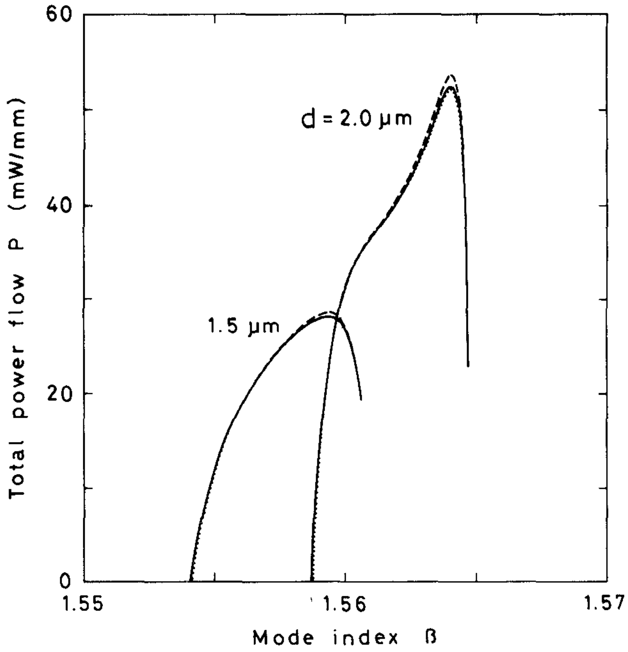


Fig. 6. Dependence of the total power flow P on the mode index β for the TM_1 mode guided by the three-layer waveguide with nonlinear cover for two film thicknesses d. The dispersion curves are plotted for two nonlinear mechanisms; $\gamma = 1$ (solid line) and $-1/2$ (dashed line), together with those for TE_1 modes (dotted line).

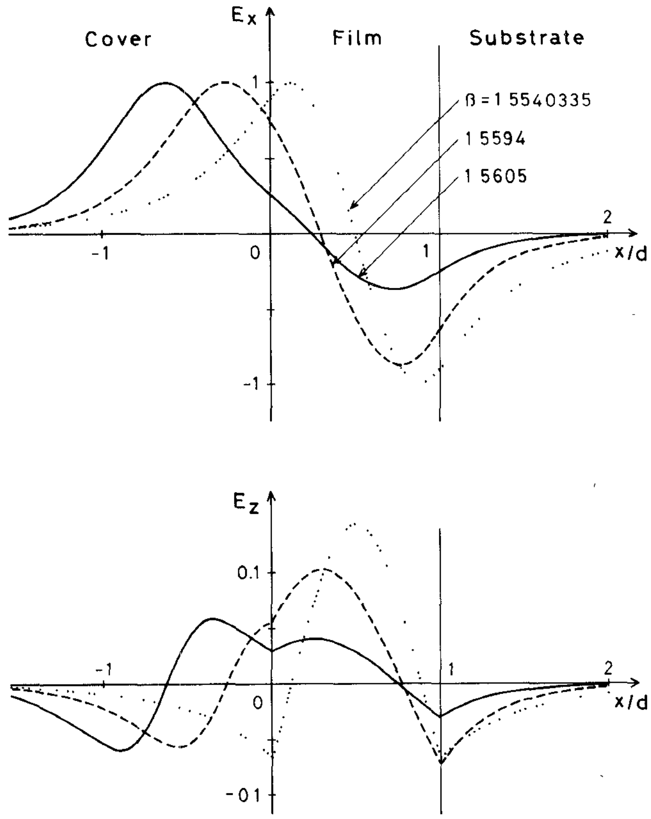


Fig. 7. Electric field distributions of the TM_1 mode in the three-layer waveguide with nonlinear cover for $d = 1.5$ μm and $\gamma = -1/2$. $\beta =$ 1.5540335, 1.5594, and 1.5605 correspond to $P = 0.0$, 28.6 (maximum power), and 22.0 mW/mm, respectively.

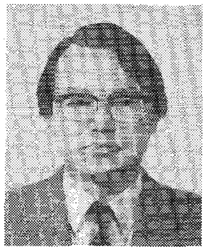
the peak of the field is not very far away from the nonlinear cover–film interface in the steady-state case calculated here. Some improved approaches are available, if necessary. One is to introduce a hypothetical nonlinear cover with $\gamma = 0$ or 1 instead of the linear cover. In that case, the field solution is expressed by the hyperbolic function "sech" [16]. Another is to transform the semi-infinite region into a finite region, as in [19]. Although non-Kerr-like nonlinear waveguides have not been investigated in this paper, it is assumed that the dispersion relations for TM waves are almost the same as those for TE waves. It is also expected that the stability of nonlinear TM waves obeys a criterion for the stability of TE waves.

IV. Conclusion

We presented a numerical method for calculating the dispersion relations for stationary nonlinear TM waves guided by nonlinear planar waveguides. The method is based on the numerical integration of the nonlinear wave equation. In this paper, the dispersion relations for TM waves in typical three-layer waveguides have been solved numerically for every mechanism of the nonlinearity and compared with those for TE waves. The electric field distributions have also been presented to facilitate understanding of nonlinear TM waves. It is shown that the dispersion curves for TM waves are similar to those for TE waves. The present method has the advantage that it can be applied to wide classes of nonlinear planar waveguides with arbitrary linear permittivity profiles and arbitrary types of the nonlinearity. The presented numerical results and method will be useful in checking the validity of new analytical techniques for solving nonlinear TM wave problems.

References

[1] M. Miyagi and S. Nishida, "Guided waves in bounded nonlinear medium (II)—Dielectric boundaries," *Rep. Res. Inst. Elect. Comm. Tohoku Univ.*, vol. B24, pp. 53–67, 1972.
[2] C. T. Seaton, Xu Mai, G. I. Stegeman, and H. G. Winful, "Nonlinear guided wave applications," *Opt. Eng.*, vol. 24, pp. 593–599, 1985.
[3] C. T. Seaton *et al.*, "Calculations of nonlinear TE waves guided by thin dielectric films bounded by nonlinear media," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 774–783, 1985.
[4] A. D. Boardman and P. Egan, "*S*-polarized waves in a thin dielectric film asymmetrically bounded by optically nonlinear media," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1701–1713, 1985.
[5] F. Lederer, U. Langbein, and H.-E. Ponath, "Nonlinear waves guided by a dielectric slab: I. TE-polarization," *Appl. Phys. B*, vol. 31, pp. 69–73, 1983.
[6] G. I. Stegeman, C. T. Seaton, J. C. Chilwell, and S. D. Smith, "Nonlinear waves guided by thin films," *Appl. Phys. Lett.*, vol. 44, pp. 830–832, 1984.
[7] H. Vach, C. T. Seaton, G. I. Stegeman, and I. C. Khoo, "Observation of intensity-dependent guided waves," *Opt. Lett.*, vol. 9, pp. 238–240, 1984.
[8] A. D. Boardman and P. Egan, "Optically nonlinear waves in thin films," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 319–324, 1986.
[9] K. Ogusu, "TE waves in a symmetric dielectric slab waveguide with a Kerr-like nonlinear permittivity," *Opt. Quantum Electron.*, vol. 19, pp. 65–72, 1987.
[10] R. K. Varshney, M. A. Nehme, R. Srivastava, and R. V. Ramaswamy, "Guided waves in graded-index planar waveguides with nonlinear cover medium," *Appl. Opt.*, vol. 25, pp. 3899–3902, 1986.
[11] K. Ogusu, "Nonlinear TE waves guided by graded-index planar waveguides," *Opt. Commun.*, vol. 63, pp. 380–384, 1987.
[12] U. Langbein, F. Lederer, T. Peschel, and H.-E. Ponath, "Nonlinear guided waves in saturable nonlinear media," *Opt. Lett.*, vol. 10, pp. 571–573, 1985.
[13] G. I. Stegeman *et al.*, "Nonlinear slab-guided waves in non-Kerr-like media," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 977–983, 1986.
[14] J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, "Numerical evidence for nonstationary, nonlinear, slab-guided waves," *Opt. Lett.*, vol. 11, pp. 315–317, 1986.
[15] M. Miyagi and S. Nishida, "TM waves in nonlinear self-focusing media," *Radio Sci.*, vol. 10, pp. 833–838, 1975.
[16] V. K. Fedyanin and D. Mihalache, "*P*-polaritons nonlinear surface polaritons in layered structures," *Z. Phys. B*, vol. 47, pp. 167–173, 1982.
[17] F. Lederer, U. Langbein, and H.-E. Ponath, "Nonlinear waves guided by a dielectric slab: II. TM-polarization," *Appl. Phys. B*, vol. 31, pp. 187–190, 1983.
[18] C. T. Seaton, J. D. Valera, B. Svenson, and G. I. Stegeman, "Comparison of solutions for TM-polarized nonlinear guided waves," *Opt. Lett.*, vol. 10, pp. 149–150, 1985.
[19] A. D. Boardman, A. A. Maradudin, G. I. Stegeman, T. Twardowski, and E. M. Wright, "Exact theory of nonlinear *p*-polarized optical waves," *Phys. Rev. A*, vol. 35, pp. 1159–1164, 1987.
[20] D. Mihalache *et al.*, "Exact dispersion relations for transverse magnetic polarized guided waves at a nonlinear interface," *Opt. Lett.*, vol. 12, pp. 187–189, 1987.
[21] R. I. Joseph and D. N. Christodoulides, "Exact field decomposition for TM waves in nonlinear media," *Opt. Lett.*, vol. 12, pp. 826–828, 1987.
[22] K. Hayata, M. Nagai, and M. Koshiba, "Finite-element formalism for nonlinear slab-guided waves," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1207–1215, 1988.
[23] K. Ogusu, "Computer analysis of general nonlinear planar waveguides," *Opt. Commun.*, vol. 64, pp. 425–430, 1987.



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