Optics Communications 350 (2015) 241–247

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Polarization dispersion characteristics analysis of optical rib waveguides in organic/polymer photonic devices

Jinkun Liao [a,*], Xiongui Tang [b], Yuan Gao [a], Wenjie Wan [a], Xiaoxia Zhang [a], Yong Liu [a], Yongzhi Liu [a]

[a] School of Opto-Electronic Information, University of Electronic Science and Technology of China (UESTC), Chengdu 610054, PR China
[b] Department of Physics, Hunan Normal University, Changsha, Hunan 410081 PR China

ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form
10 March 2015
Accepted 30 March 2015
Available online 9 April 2015

Keywords:
Integrated optics
Waveguide modulators
Electro-optical materials
Polymer waveguides
Dispersion

ABSTRACT

An efficient and high-precision single parameter variational effective index method is proposed to investigate the polarization dispersion characteristics of polymer optical rib waveguides. The transverse distribution of the effective refractive index of the waveguide is calculated by using effective index method (EI), and the distribution of optical field is approximately expressed as piecewise functions in each sub-region. The optical field with high precision is obtained by variational effective index method (VEI), and the effective index of polymer rib waveguide is computed by scalar variational formula taking the improved piecewise functions as the accurate optical field distribution. Based on the vector wave equation that governs the guided modes, the effective index is modified by perturbation method (PM) to obtain more accurate dispersion characteristics. The dispersion characteristics and transverse field distributions of the fundamental and higher order modes are analyzed in polymer multimode rib waveguides with different structure parameters and dimensions. The method has advantages such as high precision, low calculation cost and high efficiency, which provides an analytical method for the fabrication of polymeric electro-optic devices.

1. Introduction

In recent years, organic/polymer photonic devices have attracted extensive attention and became one of the active research fields of polymer photonics, due to the fabrication challenge of high-speed active photonic devices such as electro-optic (EO) modulators and tunable attenuators based on inorganic optical materials [1,2]. Compared with inorganic crystal materials, however, polymer EO materials have great advantages such as the low permittivity in the range of microwave and millimeter-wave, high EO coefficients, ultrafast response speed, and the fabrication process is relatively simple. Consequently, it is easily to match the phase velocity of light-wave with that of microwave; the half-wave voltage V_π is low and the length of EO interaction is short regularly for polymer materials that they have promising potential to fabricate high-speed ultra broadband photonic devices [3–8].

Optical waveguide structure is an indispensable building block in organic/polymer photonic devices. According to the physical and chemical properties of polymer materials, the waveguide is commonly fabricated by spin-coating and reactive ion etching, which is convenient while adopting rib waveguide structure for polymer optical waveguide. The cross-section structure of rib waveguide is depicted in Fig. 1. For simulating the properties of polymer photonic devices accurately, the optical waveguide must be analyzed and optimized theoretically. Because of the complicated structure of rib waveguide, it is impossible to obtain analytic solution, and the numerically approximate methods should be utilized for theoretical analysis. The analytical methods of optical waveguide usually are finite element method, time-domain finite difference method, finite difference beam propagation method, transfer matrix method, mode-coupling theory, and effective index method (EI) etc. [9].

For the optical rib waveguide operating at TM_{00} mode in polymer EO modulators, for example, the higher order modes and fundamental mode are stimulated together, due to the imperfection of process and non-uniformity structure. The propagation property of every mode is different from each other, which shows the so-called polarization dispersion characteristics. In this work, the optical field distribution is obtained by variational effective index method (VEI) for fundamental and higher order modes in polymer rib waveguide [10]. According to the distribution, the effective refractive index is calculated by scalar variational formula. Generally, the dispersion characteristics of optical waveguide can be analyzed by eigenvalue equation in EI and the

* Corresponding author. Fax: +86 28 83204363.
E-mail address: jkliao@uestc.edu.cn (J. Liao).

http://dx.doi.org/10.1016/j.optcom.2015.03.078
0030-4018/

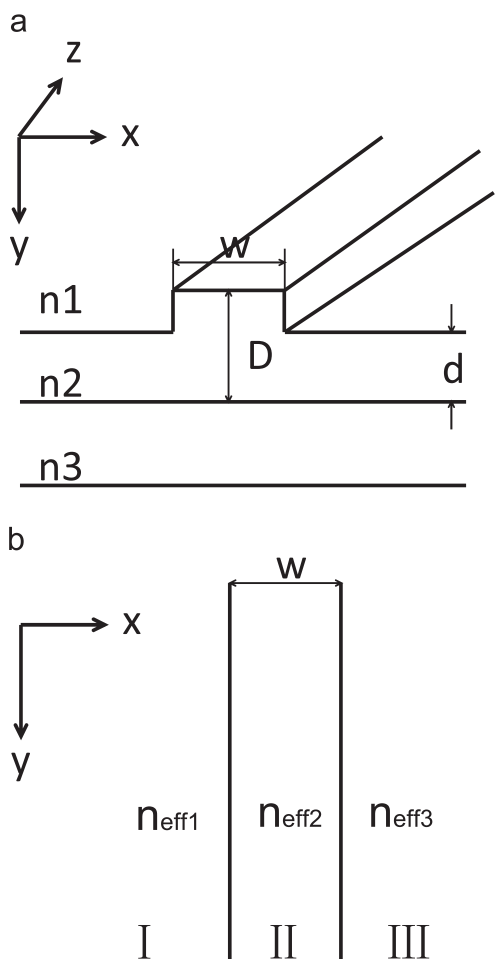

Fig. 1. Structure of optical rib waveguide and its equivalent slab waveguide (a) cross-section construction of rib waveguide, (b) equivalent slab waveguide.

calculation cost is not high, but it is difficult to obtain accurate effective index [11]. It is convenient for VEI to obtain effective index with high precision by scalar variational formula for TE modes [12–16]. While analyzing the polarization dispersion characteristics of different modes in optical waveguide, however, the vector properties of light-wave field must be considered (viz. polarization modification) especially for TM modes. The investigation indicates that the transverse field distributions and dispersion characteristics with high precision can be obtained by the method proposed in this paper. Also, the effect of structure parameters and dimensions on the dispersion can be analyzed under lower complexity.

2. Variational effective index method

Suppose the transverse analysis domain of the optical rib waveguide mentioned above is Ω. Neglecting the transverse changes of refractive index of rib waveguide as shown in Fig. 1, the dominant component of the transverse optical field distribution, Ψ, satisfies the two-dimensional scalar wave equation as follows:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+k_0^2[n^2(x,y)-n_{eff}^2]\psi=0 \tag{1}$$

where $n(x,y)$ is the transverse distribution of refractive index, n_{eff} is the effective index to be solved by eigen equation, and k_0 is the wave number in free space, respectively. By using VEI [10], optical field Ψ can be expressed as the superposition of optical fields in sub-regions, as written below

$$\Psi(x,y)=X(x)\cdot[Y_1(y)+RY_2(y)] \tag{2}$$

where $X(x)Y_1(y)$ and $X(x)Y_2(y)$ are optical field distributions in regions I, III and II respectively, and R is a variational parameter. It is not difficult to solve wave Eq. (1) in equivalent slab waveguide and regions I, III and II.The obtained solutions are as follows [9]:

$$X(x)=\begin{cases}\cos\ \phi\ \exp[\gamma_1(x+w/2)] & x<-w/2\\ \cos\ [\gamma_2(x+w/2)+\phi] & -w/2<x<w/2\\ \cos(\gamma_2 w+\phi)\exp[-\gamma_3(x-w/2)] & x>w/2\end{cases} \tag{3}$$

where

$$\gamma_1=k_0\sqrt{n_{eff}^2-n_{eff1}^2},\ \gamma_2=k_0\sqrt{n_{eff2}^2-n_{eff}^2},\ \gamma_3=k_0\sqrt{n_{eff}^2-n_{eff3}^2} \tag{4}$$

$$\phi=-\operatorname{arctg}(c_1\gamma_3/\gamma_2)+p\pi,\ (p=0,1,2,\cdots) \tag{5}$$

In Eq. (5), $c_1=n_{eff2}^2/n_{eff1}^2$ for TE modes, and $c_1=1$ for TM modes, respectively.

In regions Iand III,

$$Y_1(y)=\begin{cases}\cos(\gamma_2' d+\alpha)\exp[-\gamma_1'(y-d)] & y>d\\ \cos(\gamma_2' y+\alpha) & 0<y<d\\ \cos\ \alpha\ \exp(\gamma_3' y) & y<0\end{cases} \tag{6}$$

$$\gamma_1'=k_0\sqrt{n_{eff1}^2-n_1^2},\ \gamma_2'=k_0\sqrt{n_2^2-n_{eff1}^2},\ \gamma_3'=k_0\sqrt{n_{eff1}^2-n_3^2} \tag{7}$$

$$\alpha=-\operatorname{arctg}(c_2\gamma_3'/\gamma_2')+q\pi,\ (q=0,1,2,\cdots) \tag{8}$$

In region II,

$$Y_2(y)=\begin{cases}\cos(\gamma_2'' D+\beta)\exp[-\gamma_1''(y-D)] & y>D\\ \cos(\gamma_2'' y+\beta) & 0<y<D\\ \cos\ \beta\ \exp(\gamma_3'' y) & y<0\end{cases} \tag{9}$$

$$\gamma_1''=k_0\sqrt{n_{eff2}^2-n_1^2},\ \gamma_2''=k_0\sqrt{n_2^2-n_{eff2}^2},\ \gamma_3''=k_0\sqrt{n_{eff2}^2-n_3^2} \tag{10}$$

$$\beta=-\operatorname{arctg}(c_2\gamma_3''/\gamma_2'')+q\pi,\ (q=0,1,2,\cdots) \tag{11}$$

In Eqs. (8) and (11), $c_2=n_2^2/n_1^2$ for TM modes, $c_2=1$ for TE modes, respectively. As shown in Fig. 1, the width of rib area is w in above expressions, and the refractive indices of upper cladding, core layer and lower cladding are n_1, n_2 and n_3, respectively. The heights of core layer and rib area are d and D. Clearly, $H=d$ in regions Iand III, $H=D$ in region II, respectively. The effective indices of the three regions, n_{effi} $(i=1,2,3$ corresponds to three distinct regions in Fig. 1), i.e. the transverse distribution of effective index, can be obtained by solving the eigenvalue equation. The modes of optical rib waveguide are TE_{pq} and TM_{pq}. Here p is the number of zero points in lateral and q the number of zero points in vertical, respectively.

To determine the variational parameter R, Eq. (1) is multiplied by Ψ, then integrated in transverse analysis domain Ω. Substituting Eq. (2) into Eq. (1), a second-order algebraic equation satisfied by R is deduced by simple manipulations. The calculation shows that there are two solutions for the variational parameter, and the root having smaller absolute value should be taken as the unique root of R. Substituting the R into Eq. (2), the transverse optical field distribution with high precision is obtained.

The transverse field distributions of fundamental and higher order modes have been calculated for TM modes by VEI, and the corresponding optical intensity distributions are shown in