The Improvement of Single-mode Condition of SOI Optical Rib Waveguide

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Abstract: The devices of rib waveguides on SOI with large cross-section are widely used in modern communication system. It is necessary to verification the single-mode condition proposed in historical papers. The scalar finite difference beam propagation method is used to solve the guide modes supported by rib waveguides. It is verified that the precision of single-mode condition in horizontal direction can reach better accuracy if the constant in equation is changed from 0.3 to 0.23.

1. Introduction

The rib optical waveguide devices are widely used in integrated optical systems [1,2,3]. For the coupling efficiency between optical devices, these devices are usually designed as single-mode ones. For the three layers planar waveguide, if the refractive index difference between the guide-layer and the cladding-layer is large, as in SOI (Silicon on Insulator) system, the single-mode condition is very strict. The equations about single-mode conditions appeared in historical papers are as follows [4].

$$2b\sqrt{n_1^{\ 2}-n_2^{\ 2}}\geq 1 \tag{1}$$

$$0.5\leq r<1.0 \tag{2}$$

$$\frac{a}{b}\leq 0.3+\frac{r}{\sqrt{1-r^2}} \tag{3}$$

The letters in (1) represent the material parameters and geometry parameters.Fig.1 shows the cross section of the rib guide. The rib width is designated as $2a\lambda$ and the inner rib height is $2b\lambda$ where λ is the free-space optical wavelength. The outer regions of the rib have a thickness of $2br\lambda$ where r is the fractional height of the side regions compared to the rib center(the outer-inner ratio). The three dielectric materials have refractive indices of n_0, n_1 and n_2, respectively.

In this paper, the modes of rib waveguide will be calculated with finite difference beam propagation method (FDBPM) and the result shows that if the constant 0.3 in (1c) is changed to 0.23, the single-mode condition will be more strictly.

2. The Modes of Rib Waveguide

The 3-D rib-guide modes are denoted as HE_{nm} and EH_{nm} where $n,m=0,1,2,\cdots$, with HE being horizontally polarized and EH being vertically polarized. The index m and n are for multi-mode waveguide [5]. In practice, however, the single-mode devices are designed, so the (1) are given to point how to get single-mode device.

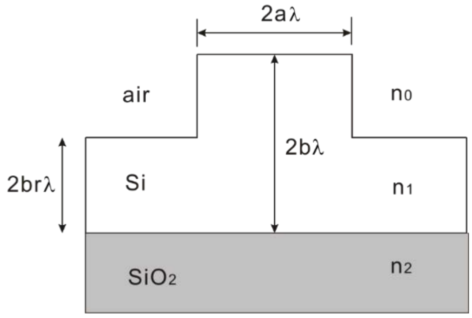

Fig. 1 Cross-section of rib waveguide

The analysis is applicable to rib guides with a large cross section satisfying the condition (1a). If equation (1b) is satisfied, higher modes in the vertical direction will be cut off because the high-order modes in the central rib section will be coupled to the fundamental mode of the slab section which becomes leaky for $r > 0.5$. Condition (1b) guarantees single-mode operation of the rib in the vertical direction. The waveguide with $r > 0.5$ means that the so-called deeply etched ribs are not considered here.

Equation (1c) is the further restrict condition for single-mode waveguide. Its inferring is based the effective-index method (EIM). But the EIM only deals with two modes, so it is necessary to verify the condition (1c) with another numeral method. This processing will be showed in the third section followed.

3. The Verifying of Single-mode Condition by FDBPM

The finite difference beam propagation method is widely used in the design of optical waveguide. The discussion in detail about this method can refer to literature [6]. The FDBPM used here is one type of mode solver. The wave pattern including multi-modes fields is input to the front of waveguide, the output pattern at the end of waveguide is analyzed by Fourier method. If the waveguide is single-mode one, after the long distance of device, the stable single-mode field should be observed, on the contrary, for the multi-mode waveguide, the output pattern is not stable and always changed.

The parameters of waveguide example adopted here are: $n_1 = 3.44$, $n_2 = 3.34$, $\lambda = 1.55\mu m$,the geometric parameters are $w = 2a\lambda = 2\mu m$, $r = 0.55$. When using FDBPM, *w* and *r* are stationary while the *b* or total height (*h*) is changed from $h = 5.4$ to $h = 1.6$, in several *h*, after $655\mu m$ propagation, the spread-analysis of output patterns are as Fig.2 and Fig.3. It is obviously that when $h = 2.2\mu m$ the device is most near to single-mode and the 0.3 constant in (1c) can be accordingly changed to 0.23 for more accurate.

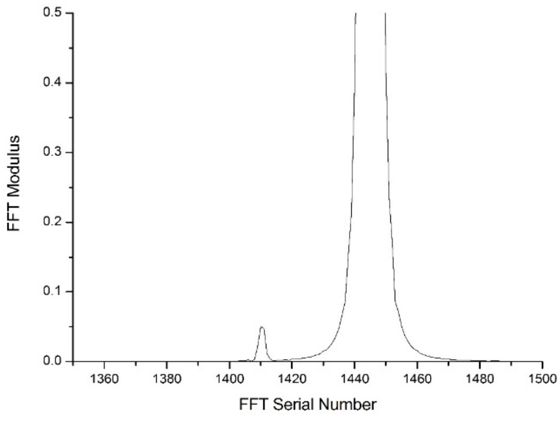

Fig.2 Fourier spectrum of output pattern when $h = 2.3$

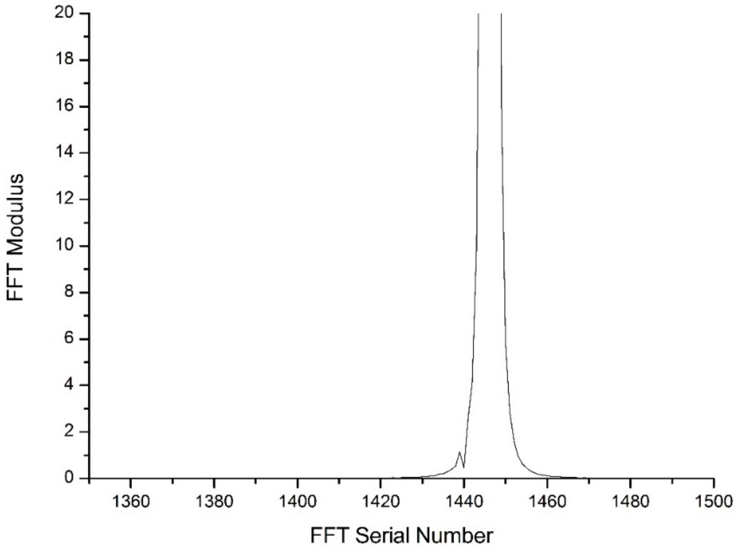

Fig. 3 Fourier spectrum of output pattern when $h = 2.2$

4. Summary

In this paper, the FDBPM is used to verify the single-mode condition. The result shows that a more restrictive condition was abstained, namely, $a/b \le 0.23 + r/\sqrt{1-r^2}$. It should be pointed out emphatically that this condition is not for deep-etched waveguide.

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