Silicon Photonics
矽光子學
4 Silicon-On-Insulator (SOI) Photonics (A)

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- 4.2 SILICON-ON-INSULATOR WAVEGUIDES
- 4.3 THE EFFECTIVE INDEX METHOD OF ANALYSIS

4.1 INTRODUCTION

INTRODUCTION

- Integrated Optics in Silicon: a combination of Technological and Cost reasons.
- Cost Issues: the cost for silicon and SOI is lower than the III-V compounds or the insulator lithium niobate ($LiNbO_3$).
- Silicon: a well-understood and robust material.
- The Processing of Silicon: developed by the electronics industry to a level that is more than sufficient for most integrated optical applications.

INTRODUCTION

- Minimum Feature Size: 1-2 microns
- Silicon microelectronics continues to advance, new and improved processing becomes available.
- Exception: the occasional requirement for a very compact structure in silicon, grating photonic wire, etc.
- Grating: owing to the large refractive index of silicon (~3.5), needs to have a submicron feature size for applications at wavelengths at which silicon is transparent (> 1.1 μm approx.) .

INTRODUCTION

- Alternative Technology: Silica(SiO_2)-based integrated optics, is lower cost, but is a passive material with little prospect for active devices such as sources, detectors, or optical modulators.
- One Technological Issue: Possibility of optical phase and amplitude modulation in silicon.
- Refractive Index Modulation: possible via several techniques and free carrier injection is the most efficient.

INTRODUCTION

- Free Carrier Injection: not a fast modulation mechanism, compared to the field-effect mechanisms (linear electro-optic (Pockels) effect in lithium niobate at operating speeds of several tens of gigahertz). However, it is sufficient for many communications and sensor applications.
- Carrier Injection Modulators in SOI: currently are limited to modulation bandwidths of the order of a few tens of megahertz, although this is not a fundamental limit and it will be discussed later in more detail.

INTRODUCTION

- Pockels Effect: not observed in silicon owing to the Centro-symmetric nature of the crystal structure.
- Sources and detectors (beyond 1.1 μm) in silicon: have not been reported with sufficient efficiency to make them commercially viable as yet, but this is a current active research topic for many groups around the world.
- The possibility of accurate micromachining of silicon has meant that sources and detectors can be accurately aligned to silicon waveguides in a hybrid circuit, and silicon sources and detectors will need to be very cost-effective to displace this approach, or offer very significant improvements in performance.

4.2 SILICON-ON-INSULATOR (SOI) WAVEGUIDES

SOI Waveguide

- **Silicon Guiding Layer (Device Layer): typically a few micrometers in thickness.**
- **Buried Silicon Dioxide (Buried Oxide Layer): typically half a micron to act as the lower cladding layer to prevent the field associated with the optical modes from penetrating the silicon substrate below (thicker than the evanescent fields associated with the mode).**
- **Surface Oxide Layer (Optional): passivation layer.**
  - **Asymmetrical ⇨ Symmetrical**

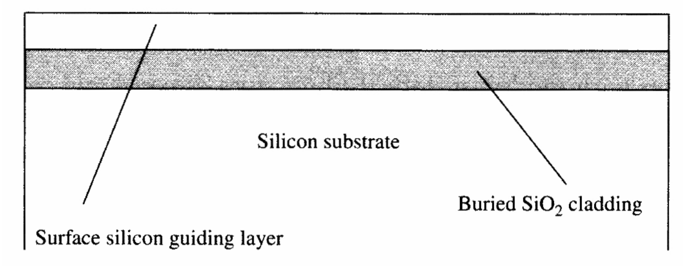

Figure 4.1 SOI planar waveguide

SOI Waveguide

- **Three-Layer Planar Waveguide: Confinement in one dimension**
- **By etching planar waveguide: Confinement in two dimensions**
  - **Rib Waveguide**
  - **Channel Waveguide (silicon photonic wire, or nanowire)**

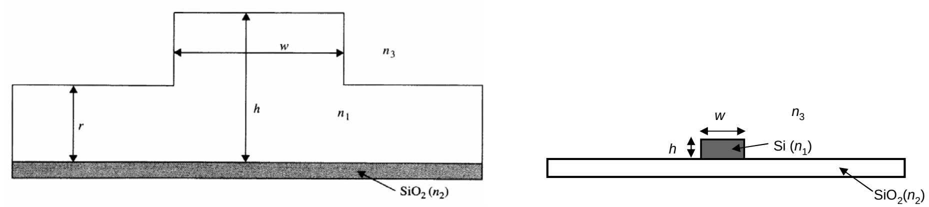

Figure 4.2 (A) Rib waveguide geometry (B) Channel waveguide geometry

4.2.1 Modes of Two-dimensional Waveguides

Modes of Two-dimensional Waveguides

- In a rectangular waveguide there exist two families of modes, the *HE* mode and the *EH* modes. In common with the skew modes of an optical fiber, these are mostly polarized in the *TE* or *TM* directions, usually referred to as the E^x or E^y modes depending on whether they are mostly polarized in the *x* or *y* direction.
- Two subscripts are introduced to identify the modes as E_p or E_q, where the integers *p* and *q* represent the number of field maxima in the *x* and *y* directions respectively. These modes are also referred to as $HE_{p,q}$ and $EH_{p,q}$ modes. Hence the fundamental modes are referred to as $E^x_{1,1}$ and $E^y_{1,1}$. This is probably the most common convention.
- However, in some convention for rectangular waveguides, the fundamental modes are referred to as $E^x_{0,0}$ and $E^y_{0,0}$ (or $HE_{0,0}$ and $EH_{0,0}$). Hence some care must be taken to indicate the labeling convention used.

4.3 THE EFFECTIVE INDEX METHOD OF ANALYSIS

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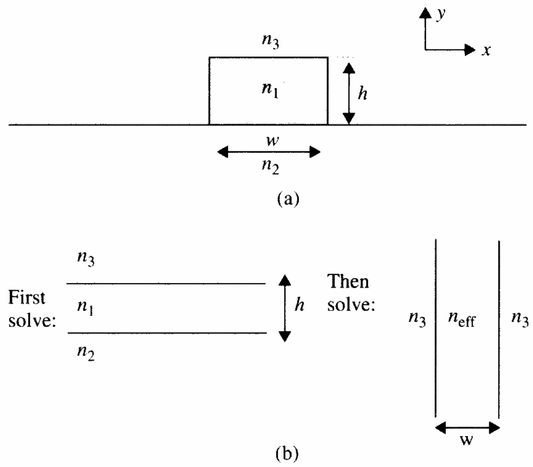


Figure 4.3 (a) Generalized two-dimensional waveguide. (b) Decomposition into two imaginary planar waveguides

4.3 THE EFFECTIVE INDEX METHOD OF ANALYSIS

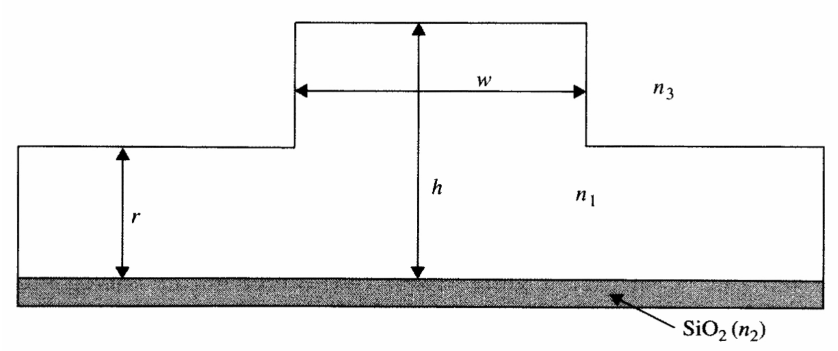
- The effective index is used to find approximate solutions for the propagation constants of two-dimensional waveguides.
- The approach to finding the propagation constants for the waveguide shown is to regard it as a combination of two planar waveguides, one horizontal and one vertical.
- We then successively solve the planar waveguide eigenvalue equations first in one direction and then the other, taking the effective index of the first as the core refractive index for the second.

Important Note

- If we are considering an electric field polarized in the *x* direction (TE polarization), then when solving the three-layer planar waveguide in the *y* direction we use the TE eigenvalue equation.
- However, when we subsequently solve the vertical three-layer planar waveguide, we must use the TM eigenvalue equation because, with respect to this imaginary vertical waveguide, the field is polarized in the TM direction.

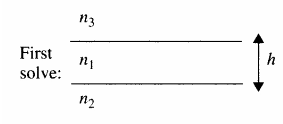
Example

- Find the effective index, N_{wg}, of the fundamental TE mode of the rib waveguide for w = 3.5 μm, h = 5 μm, r = 3 μm, n_1 = 3.5, n_2 = 1.5, n_3 = 1.0 at the operating wavelength of 1.3 μm.



Solution (I)

- Decompose the rib structure into vertical and horizontal planar waveguides, as shown in Figure 4.3b
- Solving equation (TE)



$$[k_0 n_1 h \cos\theta_1 - m\pi] = \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1 - (n_2/n_1)^2}}{\cos\theta_1}\right] + \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1 - (n_3/n_1)^2}}{\cos\theta_1}\right]$$

for the h = 5 μm (guide) and m = 0 yields a propagation angle of 87.9º (1.53456 radians).

Solution (II)

- Therefore the effective index of the waveguide region is given by:

$$\beta = n_1 k_0 \sin\theta_1 \qquad n_{effg} = \frac{\beta}{k_0} = n_1 \sin\theta_1 = 3.4977$$

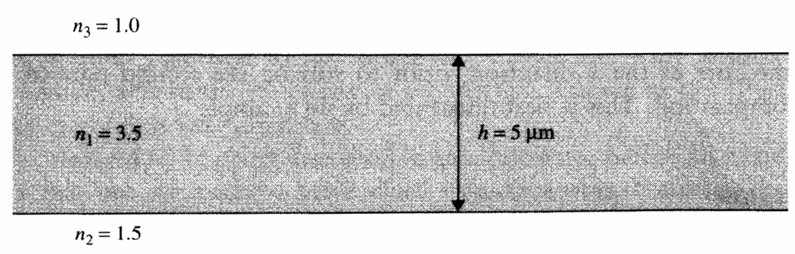
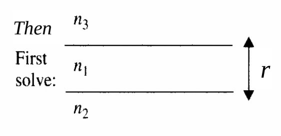


Figure 4.4 First planar waveguide of the decomposed rib structure of Figure 4.2

Solution (III)

- Solving equation (TE)

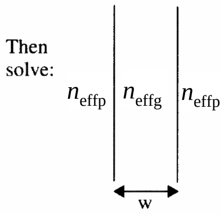
$$[k_0 n_1 r\cos\theta_1 - m\pi] = \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1-(n_2/n_1)^2}}{\cos\theta_1}\right] + \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1-(n_3/n_1)^2}}{\cos\theta_1}\right]$$



for the r = 3 μm (side) and m = 0 yields a propagation angle of 86.595º, and an effective index for the planar region of n_{effp} = 3.4938

Solution (IV)

- Solving equation (TM)



$$k_0 n_{\text{effg}} w\cos\theta_{\text{wg}} = 2\tan^{-1}\left[\frac{\sqrt{\left(\frac{n_{\text{effg}}}{n_{\text{effp}}}\right)^2\sin^2\theta_{\text{wg}}-1}}{\left(\frac{n_{\text{effp}}}{n_{\text{effg}}}\right)\cos\theta_{\text{wg}}}\right]$$

for the w = 3.5 μm (core) and m = 0 yields θ_{wg} = 88.285º and an effective index for the planar region of N_{wg} = 3.496

Solution (V)

- *z-directed* propagation constant:

$$\beta = k_0 N_{\text{wg}} = 16.897\,\text{rad}\cdot\mu\text{m}^{-1}$$

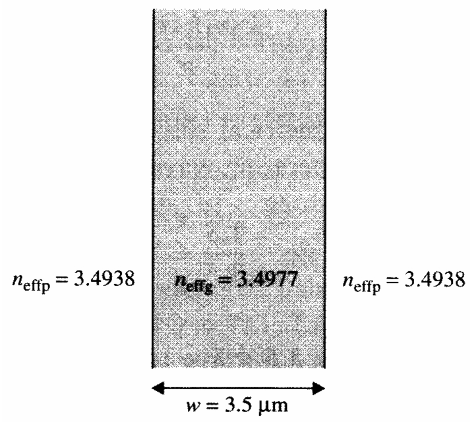


Figure 4.5 Second planar waveguide of the decomposed rib structure of Figure 4.2

Discussion

- The effective indices are all very close to the refractive index of silicon, n = 3.5: the fundamental mode is well confined - most of the power in the fundamental mode propagates within the silicon layer itself, with glancing propagation angles (according to the ray model!).
- The confinement in the vertical and horizontal directions is very different: In the vertical direction, the refractive indices are very different, resulting in high confinement, but in the horizontal direction the effective indices are much closer.
- The effective index method is an approximation, and hence there is the question of accuracy. It becomes inaccurate for complex structures, poorly confined modes, or large index steps.