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

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Outline

- **4.4 LARGE SINGLE-MODE RIB WAVEGUIDES**
- **4.5 REFRACTIVE INDEX AND LOSS COEFFICIENT IN OPTICAL WAVEGUIDES**
- **4.6 CONTRIBUTIONS TO LOSS IN AN OPTICAL WAVEGUIDE**

4.4 LARGE SINGLE-MODE RIB WAVEGUIDES

LARGE SINGLE-MODE RIB WAVEGUIDES

- For the symmetrical SOI waveguide with $h = 5\,\mu\text{m}$, $n_1 = 3.5$, $n_2 = n_3 = 1.5$, operating at $1.3\,\mu\text{m}$, the number of modes will be

$$m_{\max} = \frac{k_0 n_1 h \cos\theta_c}{\pi}$$

where
$$\theta_c = \sin^{-1}\frac{1.5}{3.5} = 25.4^\circ$$

thus
$$[m_{\max}]_{\text{int}} = \frac{2 \times 3.5 \times 5 \times 10^{-6} \cos\theta_c}{\lambda_0} = 24$$

⇨ there will be 25 modes (including $m = 0$)

LARGE SINGLE-MODE RIB WAVEGUIDES

- Single mode condition

$$\theta_c < \cos^{-1}\left(\frac{\lambda_0}{2n_1 h}\right)$$

- Maximum thickness for single mode operation in the symmetrical SOI planar waveguide

$$h < \left(\frac{\lambda_0/2}{n_1\sqrt{1-(n_2/n_1)^2}}\right)$$

⇨ approximately 0.2 μm for λ_0 = 1.3 μm

LARGE SINGLE-MODE RIB WAVEGUIDES

- Soref, et. al. 1991, analyzed with the condition

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

for the modes $HE_{p,q}$ and $EH_{p,q}$ for p = 0,1,2…, q = 0,1,2…,

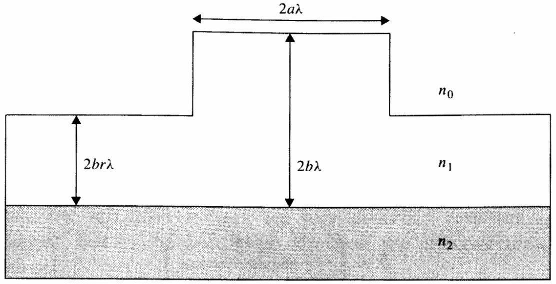
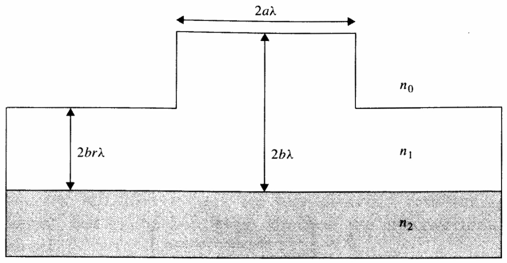


Figure 4.6 Rib waveguide definitions

LARGE SINGLE-MODE RIB WAVEGUIDES

- Only 0.5 ≤ r < 1.0 is analyzed
  - For $r \geq 0.5$, the effective indices of vertical modes in the planar region each side of the rib will become larger than those in the rib other than the fundamental mode.
  - ⇨ All modes other than the fundamental mode will be cut off



LARGE SINGLE-MODE RIB WAVEGUIDES

- Single-mode condition for the aspect ratio
  - by Soref et al.

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

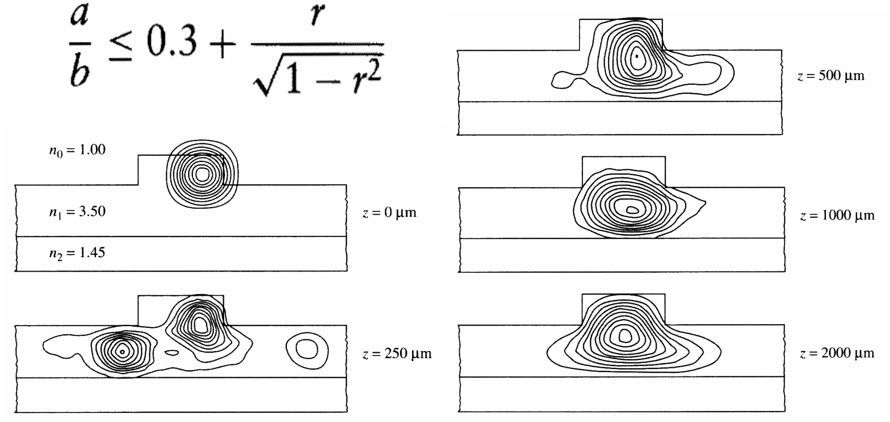


Figure 4.7 Beam propagation simulation of a rib waveguide.

LARGE SINGLE-MODE RIB WAVEGUIDES

- Single-mode condition for the aspect ratio
  - by Pogossian et al. where *c* = - 0.05

$$\frac{a}{b} \le c + \frac{r}{\sqrt{1-r^2}}$$

  - by EIM (effective index method) *c* = 0

$$\frac{a}{b} \le \frac{r}{\sqrt{1-r^2}}$$

LARGE SINGLE-MODE RIB WAVEGUIDES

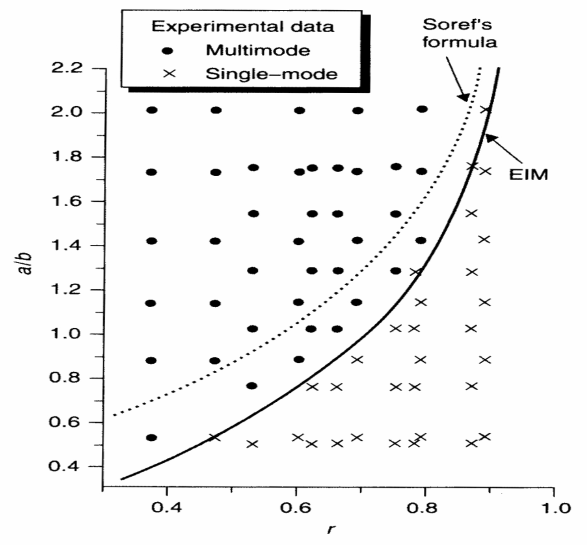


Figure 4.8 The single-mode condition compared to experimental data.

4.5 REFRACTIVE INDEX AND LOSS COEFFICIENT IN OPTICAL WAVEGUIDES

REFRACTIVE INDEX AND LOSS COEFFICIENT IN OPTICAL WAVEGUIDES

- Complex refractive index

$$n' = n_R + jn_I$$

- Recall that

$$k = nk_0 \qquad E = E_0 e^{j(kz-\omega t)}$$

thus $E = E_0 e^{j(k_0 n' z - \omega t)} = E_0 e^{jk_0 n_R z} e^{-k_0 n_I z} e^{-j\omega t}$

The term $\exp(-k_0 n_I z)$ is often redesignated as $\exp(-1/2\,\alpha\, z)$

  - α : intensity loss coefficient $I = I_0 e^{-\alpha z}$

PROPAGATION LOSS IN OPTICAL WAVEGUIDES

- Widely accepted benchmark for loss is of the order of 1 dB/cm.
  - This is because an integrated optical circuit is typically a few centimeters in length.
- Since an optical loss of 3 dB corresponds to 1/2 of the optical power, it is clear that a loss of much more than 1 dB/cm will rapidly result in a very poor signal-to-noise ratio at the detector.
- Add to this additional losses due to coupling to or from the optical circuit, or losses within the circuit not associated with propagation loss, and the situation is exacerbated.
- Losses for SOI waveguides are typically in the range 0.1-0.5 dB/cm.

4.6 CONTRIBUTIONS TO LOSS IN AN OPTICAL WAVEGUIDE

Volume Scattering

- Volume scattering
  - caused by imperfections in the bulk waveguide material, such as voids, contaminant atoms, or crystalline defects.
  - Bulk material: Rayleight scattering, λ^{-4} dependence
  - Confined waves: the wavelength dependence is related to the axial correlation length of the defects
    - For correlation lengths shorter than or of the order of the wavelength, the scattering loss exhibits a λ^{-3} dependence, because the reduction of confinement for longer wavelengths partially counters the λ^{-4} relation
    - For long correlation lengths compared to the wavelength, radiation losses dominate and a λ^{-1} dependence is observed

Interface Scattering

- Interface scattering
  - due to roughness at the interface between the core and the claddings of the waveguide.
- Tien in 1971,
  - based upon the specular reflection of power from a surface. This condition holds for long correlation lengths, which is a reasonable assumption in most cases.

$$P_r = P_i \exp\left[-\left(\frac{4\pi\sigma n_1}{\lambda_0}\cos\theta_1\right)^2\right]$$

  - P_r specular reflection power, P_i incident power, σ variance of surface roughness (r.m.s. roughness), θ_1 is the propagation angle within the waveguide, and n_1 is the refractive index of the core.

Interface Scattering

- Loss Coefficient due to Interface Scattering

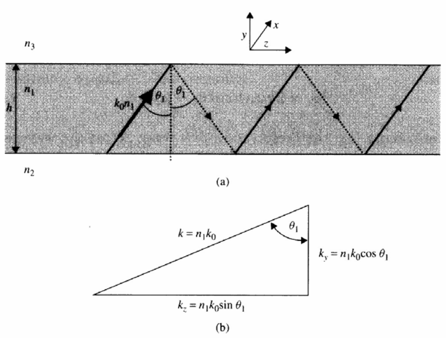
$$\alpha_s = \frac{\cos^3\theta}{2\sin\theta}\left(\frac{4\pi n_1(\sigma_u^2+\sigma_\ell^2)^{\frac{1}{2}}}{\lambda_0}\right)^2\left(\frac{1}{h+\frac{1}{k_{yu}}+\frac{1}{k_{y\ell}}}\right)$$

- σ_u and σ_l: surface roughness of upper and lower surfaces, respectively
- k_{yu} and k_{yl}: decay constant of upper and lower surface , respectively
- h: waveguide thickness

Example

- Consider a planar waveguide:

  $n_1 = 3.5$, $n_2 = 1.5$, $n_3 = 1.0$, $h = 1.0$ μm, and the operating wavelength $\lambda_0 = 1.3$ μm. Let us compare the scattering loss of two different modes of the waveguide, say the TE$_0$ and the TE$_2$ modes.



Solution

- θ_1 are 80.8º (TE$_0$) and 60.7º (TE$_2$).
- Decay constant: k_{yu} and k_{yl}

$$k_{yi}^2 = \beta^2 - k_0^2n_i^2 \qquad \beta = n_1k_0\sin\theta_1$$

TE$_0$	TE$_2$
$k_{yu} = \sqrt{\beta^2 - k_0^2n_3^2} = 15.98\ \mu\text{m}^{-1}$	$k_{yu} = \sqrt{\beta^2 - k_0^2n_3^2} = 13.94\ \mu\text{m}^{-1}$
$k_{y\ell} = \sqrt{\beta^2 - k_0^2n_2^2} = 15.04\ \mu\text{m}^{-1}$	$k_{y\ell} = \sqrt{\beta^2 - k_0^2n_2^2} = 12.85\ \mu\text{m}^{-1}$

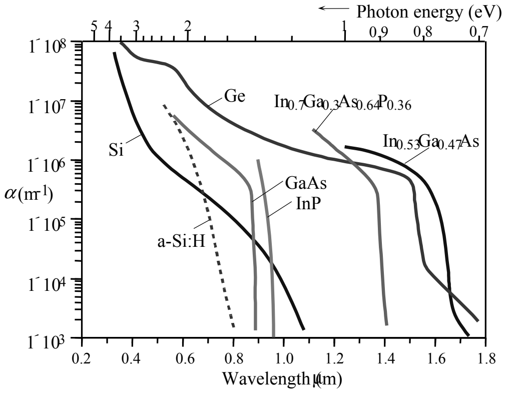
- If σ_u and σ_l are both 1 nm.

  ⇨For TE$_0$: $\alpha_s = 0.04$ cm^{-1} (0.17 dB/cm)

  ⇨For TE$_2$: $\alpha_s = 1.33$ cm^{-1} (5.78 dB/cm)

Interband Absorption

- Silicon: band edge wavelength = 1.1 μm
  - $\lambda = 1.15$ μm ⇨ attenuation = 2.83 dB/cm
  - $\lambda = 1.52$ μm ⇨ attenuation = 0.004 dB/cm



Free Carrier Absorption

- Drude-Lorentz equation: change in absorption

$$\Delta\alpha = \frac{e^3\lambda_0^2}{4\pi^2 c^3 \varepsilon_0 n}\left(\frac{N_e}{\mu_e (m^*_{ce})^2} + \frac{N_h}{\mu_h (m^*_{ch})^2}\right)$$

  - e: the electronic charge, c: the velocity of light in vacuum, μ_e: the electron mobility, μ_h: the hole mobility, m^*_{ce}: the effective mass of electrons, m^*_{ch}: the effective mass of holes, N_e: the free electron concentration, N_h: the free hole concentration, ε_0: the permittivity of free space, and λ_0: the free space wavelength.

Free Carrier Absorption

- If N_e and N_h are 10^{18} cm^{-3},

⇨ $\Delta\alpha = 2.5$ cm^{-1} (10.86 dB/cm)

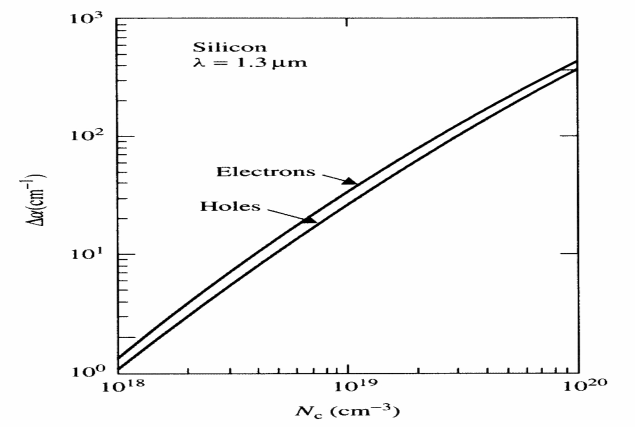


Figure 4.9 Additional loss of silicon due to free carriers.

Radiation Loss

- Waveguide defect
  - e.g., slightly damaged fabrication mask
  - Mode coupled into higher order modes and then attenuated by radiation
- Waveguide bending
  - ⇨ Chap. 6.3
- Substrate radiation
  - Buried oxide (BOX) layer should be sufficiently thick

Substrate Radiation

- Depends on the modes, polarization and wavelength
- For 1.3-1.6 μm, Buried Oxide should > 0.4 μm.
- Thinner core ⇨ thicker BOX layer

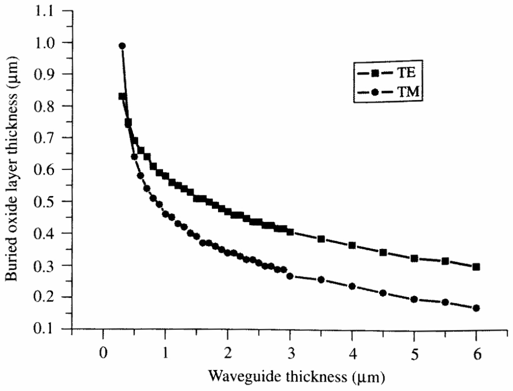


Figure 4.10 Buried oxide layer thickness vs planar SOI waveguide thickness for achieving ~ 0.001 dB/cm loss for the fundamental mode at the wavelength of 1550nm