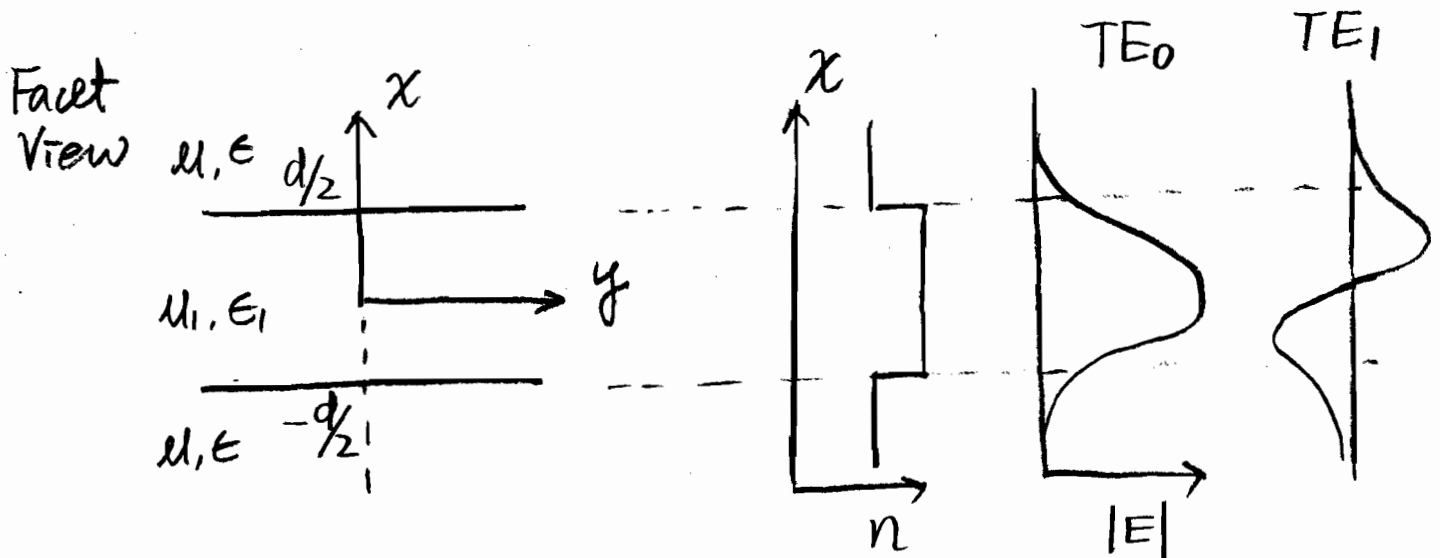
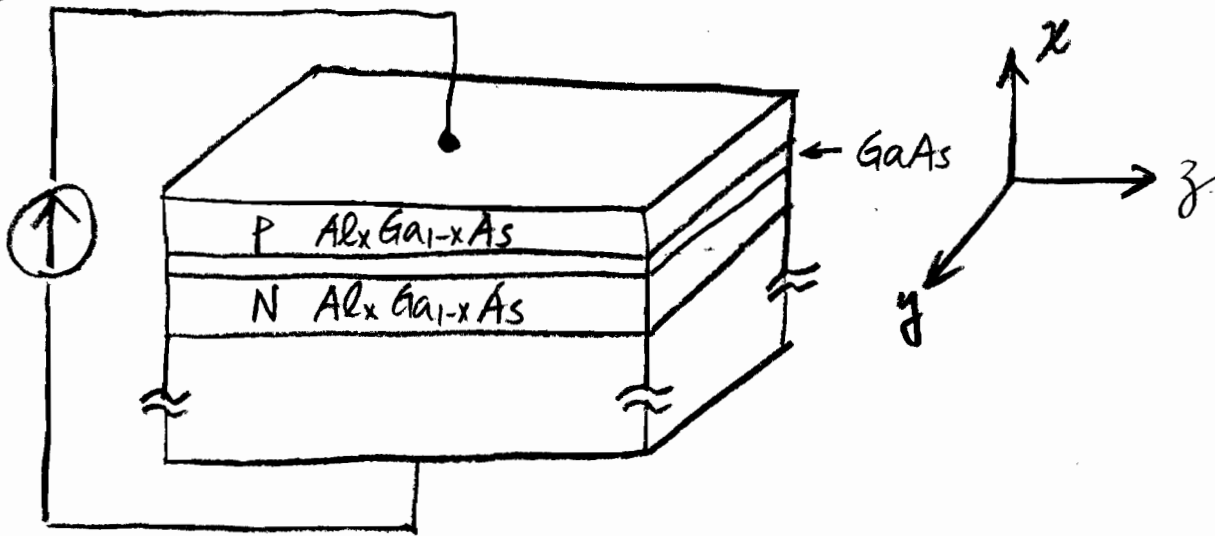


Optical Waveguide

DH forms a slab waveguide



TE (Transverse Electric) Modes

$$\begin{array}{c}
 H_x \\
 \uparrow \\
 \begin{array}{c}
 \rightarrow H_z \\
 \rightarrow \vec{E} = \hat{y} E_y \quad (E_x = E_z = 0)
 \end{array}
 \end{array}$$

TM (Transverse Magnetic) Modes

$$\begin{array}{c}
 E_x \\
 \uparrow \\
 \begin{array}{c}
 \rightarrow E_z \\
 \rightarrow \vec{H} = \hat{y} H_y \quad (H_x = H_z = 0)
 \end{array}
 \end{array}$$

Maxwell's Eq.

$$(\nabla^2 + \omega^2 \mu \epsilon) \vec{E} = 0$$

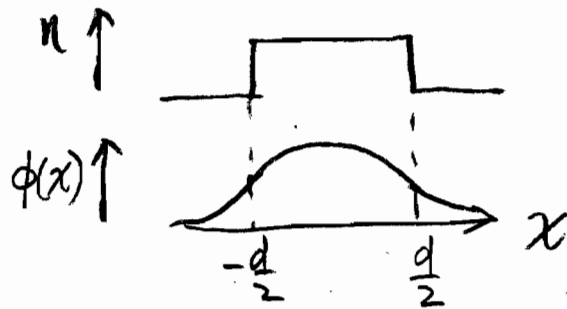
TE: $\vec{E} = \hat{y} E_y$ ($E_x = E_z = 0$)

$\frac{\partial}{\partial y} \rightarrow 0$ symmetry

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \omega^2 \mu \epsilon \right) E_y = 0$$

Similar to potential well solution

$$E_y = e^{i k_z z} \cdot \phi(x)$$



$$\phi(x) = \begin{cases} C_0 e^{-\alpha(|x| - \frac{d}{2})} & |x| \geq \frac{d}{2} \\ C_1 \cos k_x \cdot x & |x| < \frac{d}{2} \end{cases}$$

↳ for even mode, such as TE₀, TE₂

→ C₁ sin k_x x for odd modes, TE₁, TE₃

$$\Rightarrow k_x^2 + k_z^2 = \omega^2 \mu_1 \epsilon_1 \quad \dots \text{①}$$

$$-\alpha^2 + k_z^2 = \omega^2 \mu \epsilon \quad \dots \text{②}$$

$$\text{①} - \text{②}$$

$$k_x^2 + \alpha^2 = \omega^2 (\mu_1 \epsilon_1 - \mu \epsilon)$$

Matching boundary conditions.

$$\begin{cases} E_x \text{ continuous} \\ H_z = \frac{1}{i\omega\mu} \frac{\partial E_y}{\partial x} \text{ continuous} \end{cases}$$

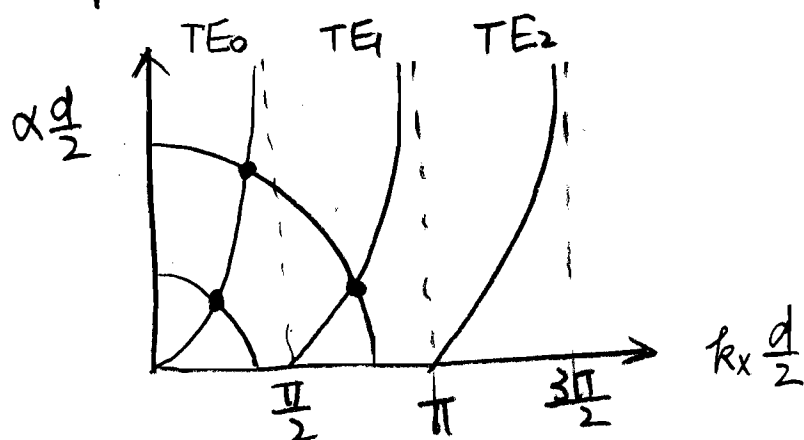
$$\Rightarrow \alpha = \frac{u}{u_1} k_x \tan(k_x \frac{d}{2})$$

Compare with QW solution

$$\alpha = \frac{m_b}{m_w} k \tan(k \frac{L}{2})$$

same eigenequation!

Graphic solution



$$\textcircled{1} - \textcircled{2} : k_x^2 + \alpha^2 = \omega^2 (\mu_1 \epsilon_1 - \mu \epsilon)$$

$$= k_0^2 \cdot c^2 (\mu_1 \epsilon_1 - \mu \epsilon) \quad ; \quad c^2 = \frac{1}{\mu_0 \epsilon_0}$$

$$= k_0^2 \left(\frac{\mu_1 \epsilon_1}{\mu_0 \epsilon_0} - \frac{\mu \epsilon}{\mu_0 \epsilon_0} \right)$$

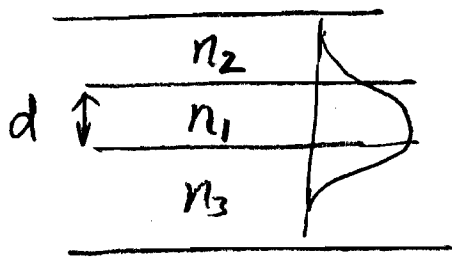
$$k_x^2 + \alpha^2 = k_0^2 (n_1^2 - n^2)$$

$$\left(k_x \frac{d}{2}\right)^2 + \left(\alpha \frac{d}{2}\right)^2 = \left(k_0 \frac{d}{2}\right)^2 (n_1^2 - n^2)$$

Single mode condition

$$\alpha \frac{d}{2} \rightarrow 0, \quad k_x \frac{d}{2} = k_0 \frac{d}{2} \sqrt{n_1^2 - n^2} < \frac{\pi}{2}$$

For general slab WG, it is customary to



define 3 dimensionless parameters:

Normalized frequency $V = k_0 d \sqrt{n_1^2 - n_3^2}$

propagation parameter $b = \frac{n_{\text{eff}}^2 - n_3^2}{n_1^2 - n_3^2}$

asymmetry parameter $a = \frac{n_3^2 - n_2^2}{n_1^2 - n_3^2}$

For symmetric slab

$$a = 0$$

single mode condition: $V < \pi$

$$k_0 d \sqrt{n_1^2 - n_3^2} \approx \frac{2\pi}{\lambda} d \cdot \sqrt{\underbrace{(n_1 + n_3)}_{\approx 2n_1} \underbrace{(n_1 - n_3)}_{\approx \Delta n}} < \pi$$

$$\Rightarrow d^2 \Delta n < \frac{\lambda^2}{8n_1}$$

Example:

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	$n = 3.385$	$> \Delta n \approx 0.205$
GaAs	$n = 3.59$	

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	$\Rightarrow d < 0.36 \mu\text{m}$ for single mode
---	--

(Vertical)
Transverse Confinement Factor

$$\Gamma = \frac{\int_{-\frac{d}{2}}^{\frac{d}{2}} |\vec{E}(x)|^2 dx}{\int_{-\infty}^{\infty} |\vec{E}(x)|^2 dx}$$

For symmetric WG with small Δn .

$$\Gamma \approx \frac{V^2}{2 + V^2}$$

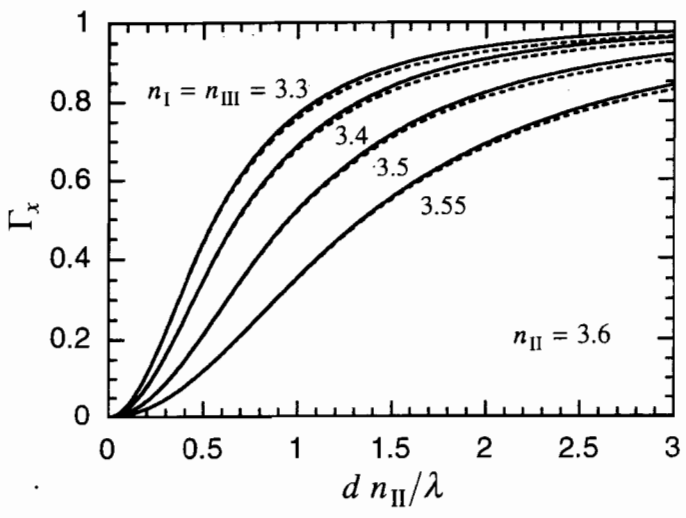
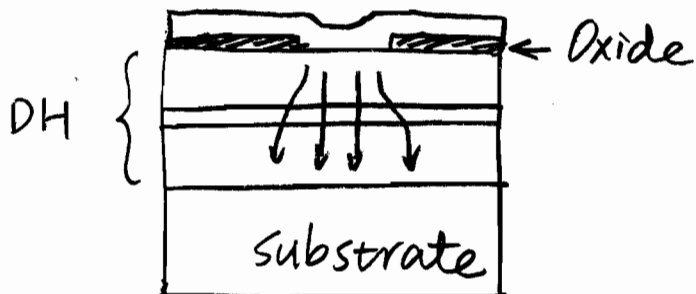


FIGURE A3.3 Comparison between the exact confinement factor (solid curve) and the approximate formula (A3.15) (dashed curve) for several values of the cladding index as a function of the guide thickness for the fundamental slab mode.

Typical Laser Structures

(cross-sectional view at facet)

Gain-guided Laser



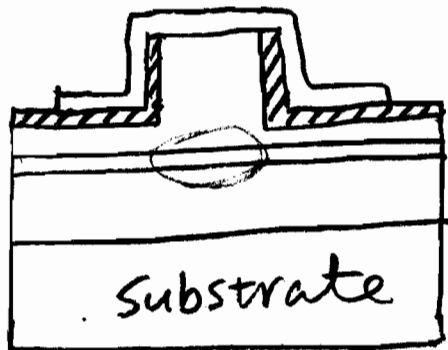
- Easy to fabricate
- Active region wider than oxide opening due to current spreading.

$W_{eff} \sim 10 \mu m$

- $I_{th} \propto W$
→ Higher threshold
- Mode
→ Easy to generate high-order lateral mode

Index-guided laser

① Ridge-waveguide laser

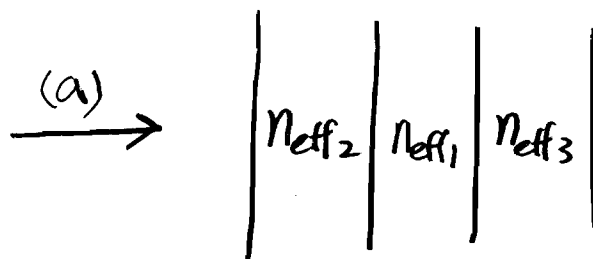
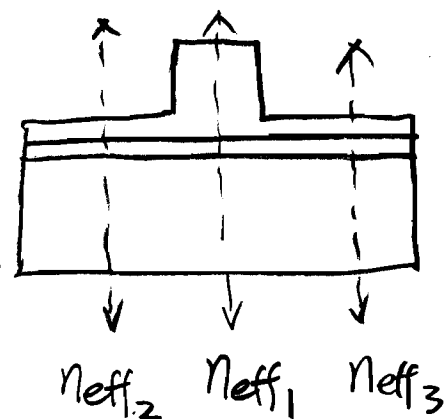


- Weak index guiding
 $\Delta n_{lateral} \sim 10^{-2}$
- Real index guiding
→ More stable mode
- Some current spreading
- Easy to fabricate
→ One epitaxial growth

Typical analysis for 2-D waveguide

Effective Index Method

(a) Calculate n_{eff} along vertical cross-section at center and surrounding regions:

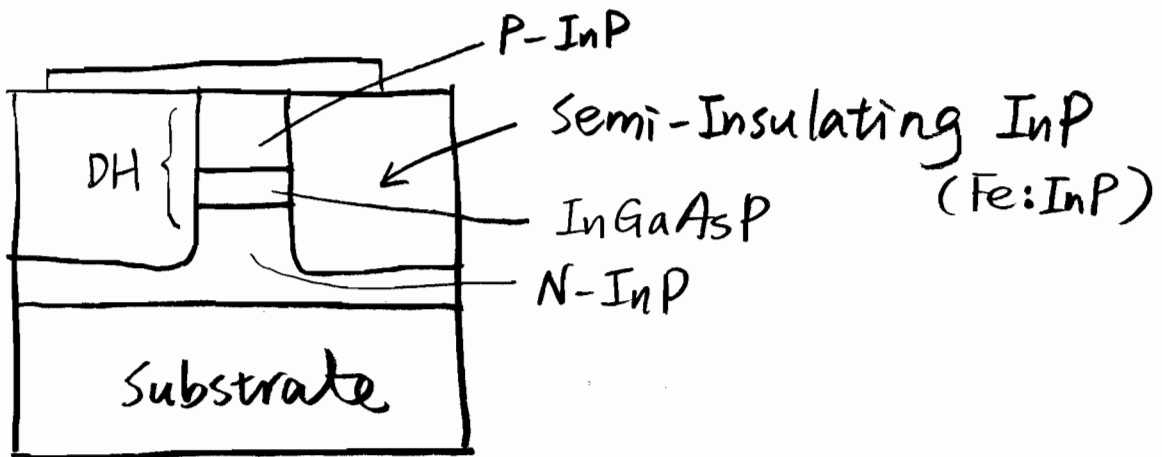


↓ (b)

Solve vertical slab for final n_{eff}

(b) Solve vertical slab waveguide for n_{eff}

② Buried Heterostructure



- Heterostructures all around active region
- No current spreading \rightarrow low I_{th}
- Tight lateral guiding (larger Δn)
- Narrow laser width, $w \sim 1 \mu m$
 \rightarrow low I_{th}
- Low parasitic capacitance \rightarrow higher RC bandwidth
- Require multiple epi growth (2 or 3)
- Works well for InP/InGaAsP materials