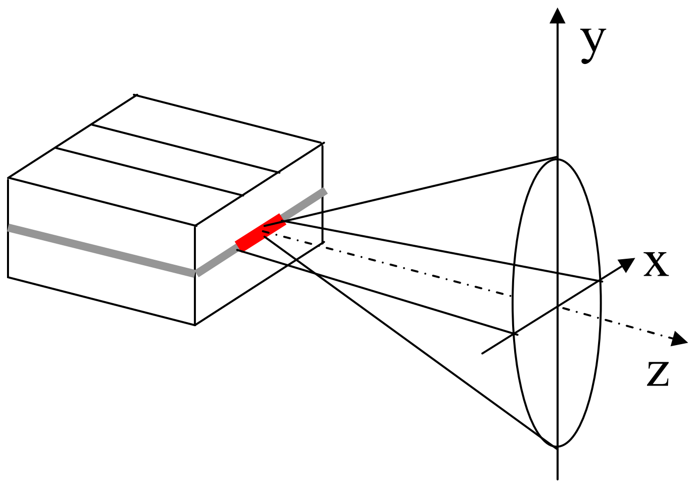
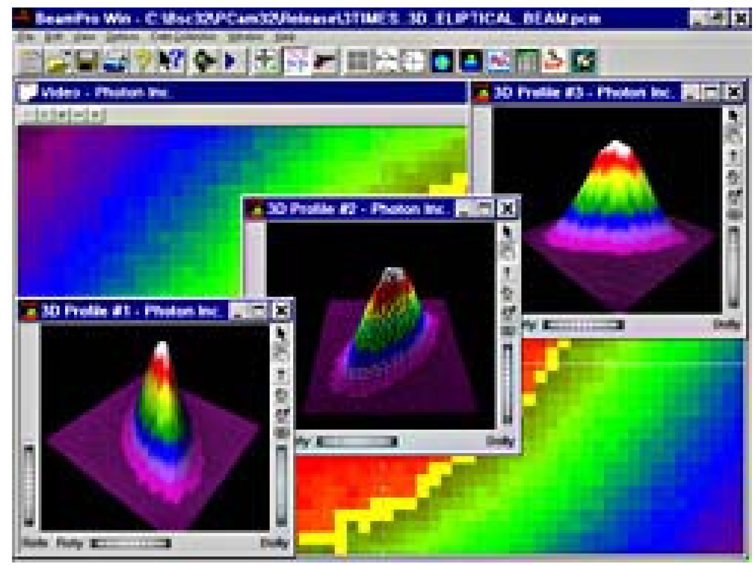
# Diode laser emission



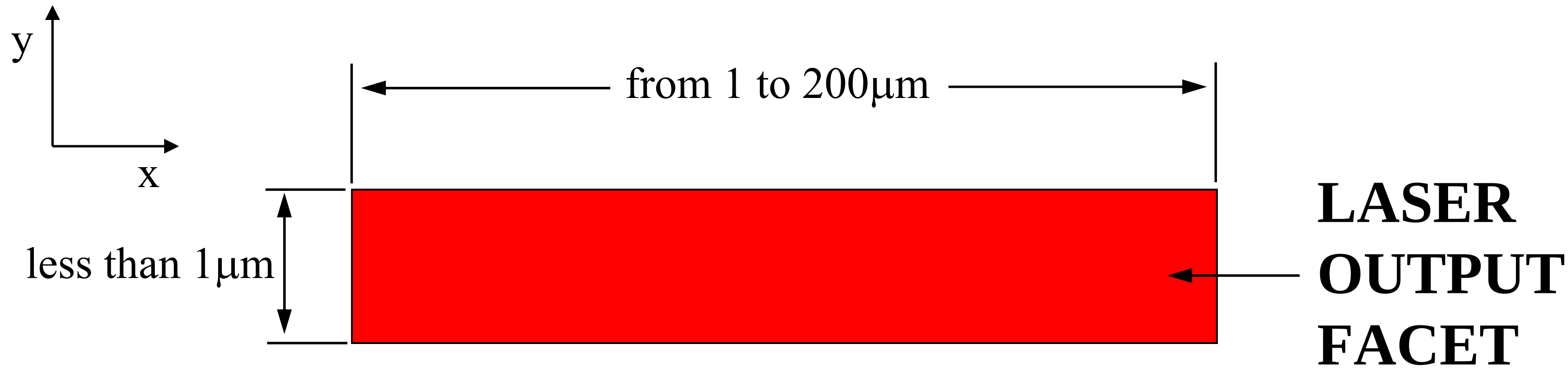



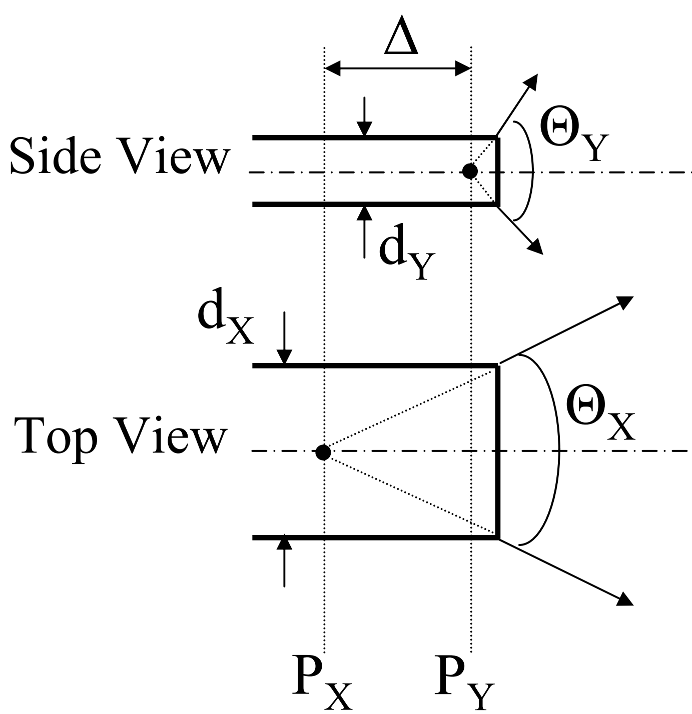
**Diode laser emission has oblong cross-section.**

**Y-axis with large divergence angle is called fast axis**

**X-axis with smaller divergence angle is called slow axis**

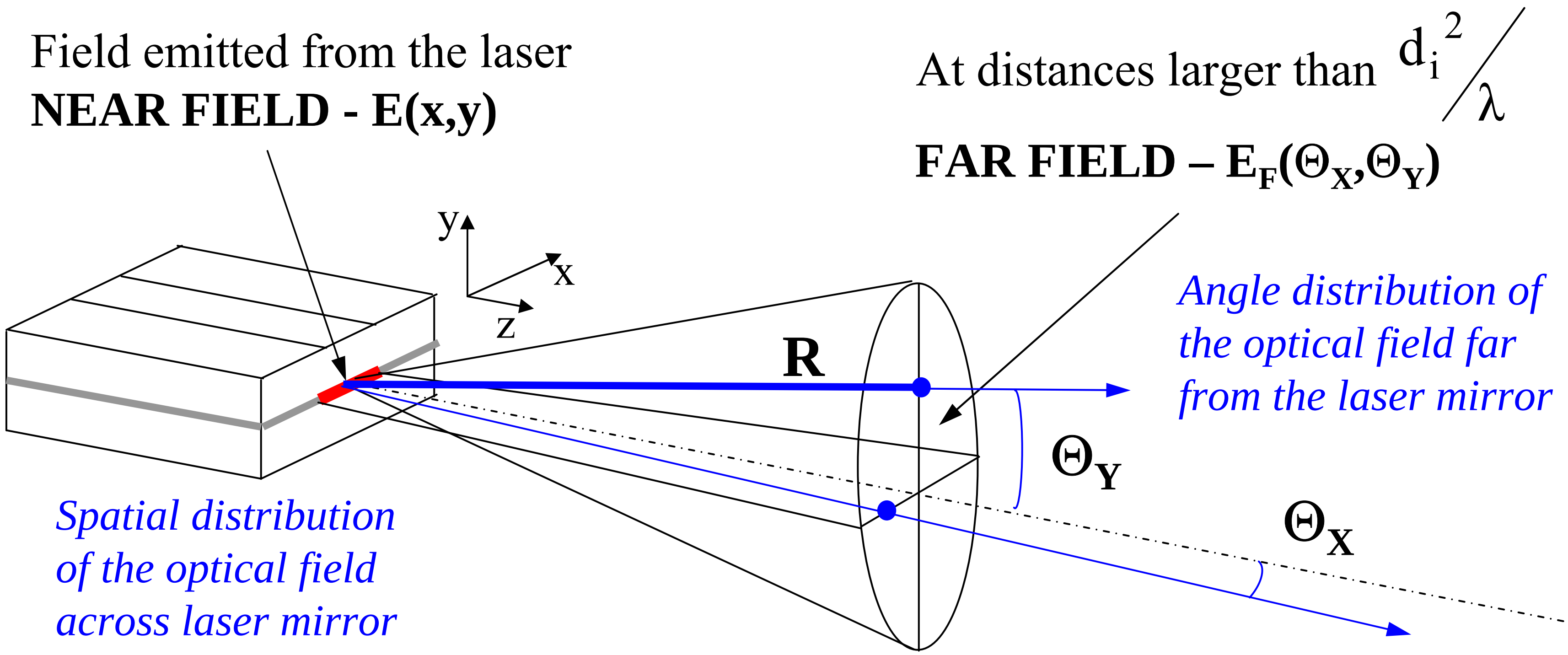
# Laser emission: beam divergence and astigmatism



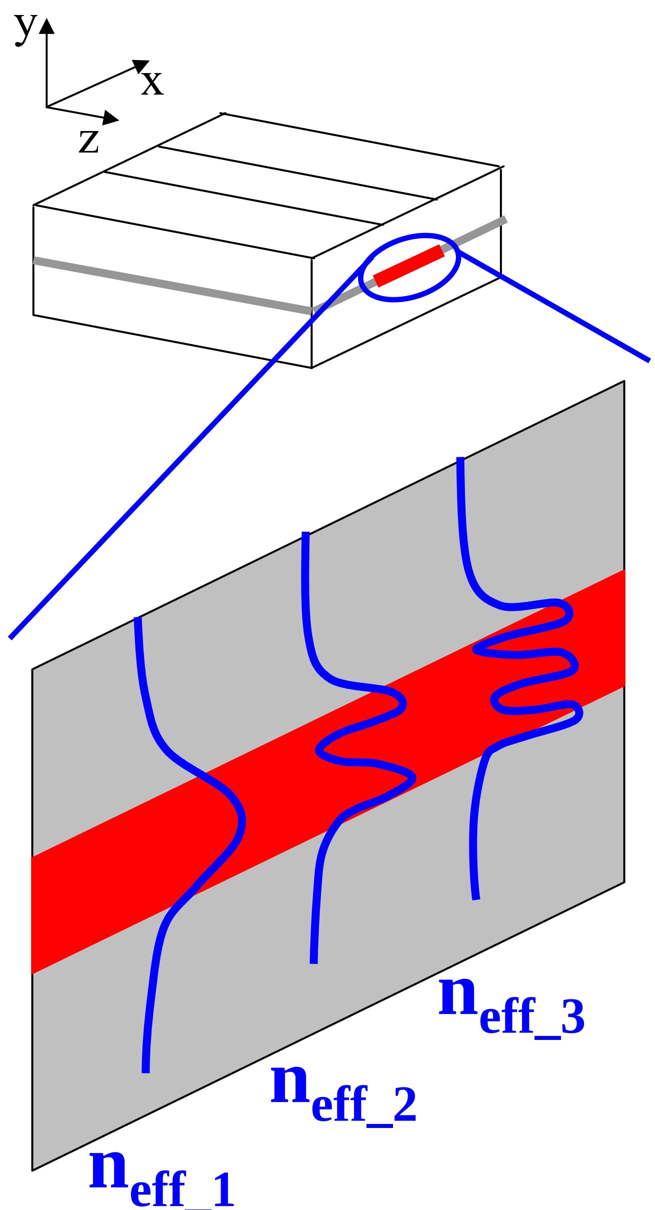

Beam emitted from a small facet is equivalent to the beam emitted by an imaginary point source P. When $d_X$ is larger than $d_Y$ the distance between $P_X$ and $P_Y$ can be nonzero. This phenomenon is called astigmatism, and the distance Δ between $P_X$ and $P_Y$ is the numerical description of astigmatism.

# Laser emission: far and near field emission patterns




Near field pattern uniquely determines far field pattern

# Laser near field




Size of the laser mirror (at least in y direction) is comparable with wavelength of light and wave optic analysis techniques must be used.

Main result of this analysis is that laser near field pattern can take shapes only from certain discrete set of special shapes called modes. No other shapes of near field pattern are allowed.

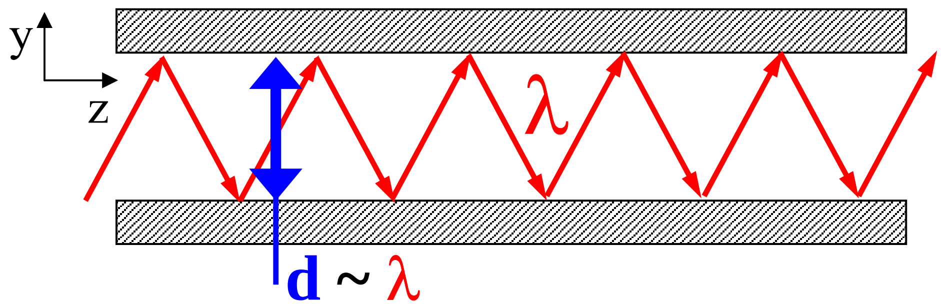
This effect is very similar in nature to quantization of the energy states of electron in atom.

Each laser mode is characterized by certain number – effective refractive index ($\mathbf{n_{eff}}$). This number determines mode shape and its group velocity.

Number of possible (allowed) near field shapes (modes) is given by laser wavelength, refractive indexes of all layers and actual sizes of layers.

# Nature of discreteness of the possible near field shapes

Consider light propagating in between of two perfect mirrors (metallic with 100% reflection)




Because of total reflection from the mirror the energy transfer will occur only in direction z and in direction y standing wave must be formed.

Standing wave condition for perfect mirrors is: $d = \frac{\lambda_y}{2} \cdot m, \quad m = 1,2,3...$

We used $\lambda_y$ because only y-projection of the light wave vector matters in y-direction:

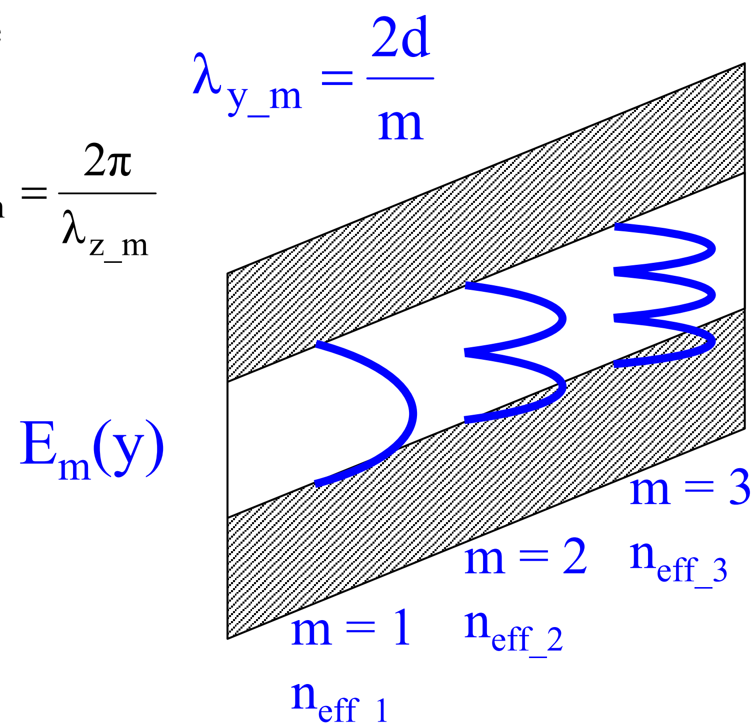
$$k^2 = k_{y\_m}^2 + k_{z\_m}^2, \quad k_{y\_m} = \frac{2\pi}{\lambda_{y\_m}} \quad \text{and} \quad k_{z\_m} = \frac{2\pi}{\lambda_{z\_m}}$$

Resulting optical field will look like:

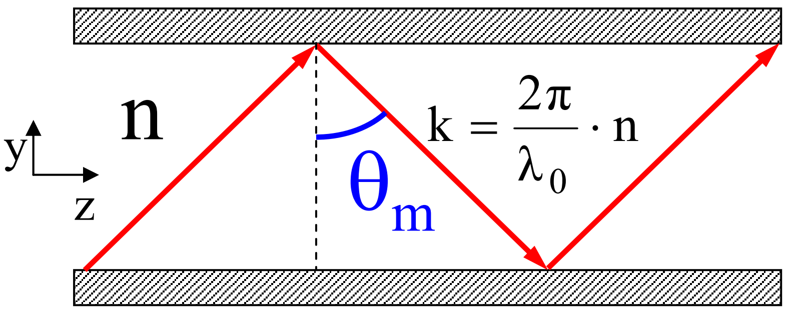
$$E(y,z) = E_m(y) \cdot \exp(j \cdot (\omega \cdot t - k_{z\_m} \cdot z)),$$

where $k_{z\_m} = \frac{2\pi}{\lambda_0} \cdot n_{eff\_m}$    * $\lambda_0$ –wavelength in vacuum

$$E_m(y) \propto \begin{cases} \cos(k_{y\_m} \cdot y), & m = 1 + \text{even number} \\ \sin(k_{y\_m} \cdot y), & m = 1 + \text{odd number} \end{cases}$$



# Physical meaning of the effective refractive index



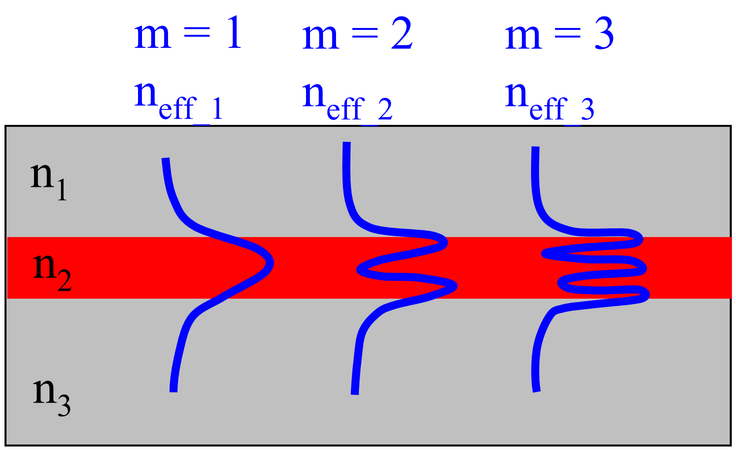

$$k_{z\_m} = k \cdot \sin(\theta_m) = \frac{2\pi}{\lambda_0} \cdot n \cdot \sin(\theta_m) = \frac{2\pi}{\lambda_0} \cdot n_{eff\_m}$$

$$k_{y\_m} = k \cdot \cos(\theta_m) = \frac{2\pi}{\lambda_0} \cdot n \cdot \cos(\theta_m) =$$

$$= \frac{2\pi}{\lambda_0} \cdot n \cdot \sqrt{1 - \sin^2(\theta_m)} = \frac{2\pi}{\lambda_0} \cdot \sqrt{n^2 - n_{eff\_m}^2}$$

* Mode effective refractive index determines group velocity for a given mode

In semiconductor lasers no metallic mirrors are available (huge loss would have appeared). The waveguide is formed by stack of semiconductors with different refractive indexes. Optical field can propagate in semiconductors as opposed to metals. As a result, we will not have the luxury of zero optical field on the physical surface of the mirrors.

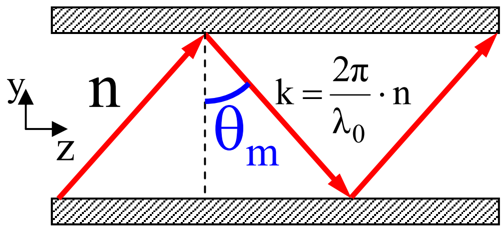



Standing wave in y-direction will be formed again. Optical field will not be fully confined in region with refractive index $n_2$ but will have exponentially decaying tails in regions $n_1$ and $n_3$. Effective refractive index can be understood as being weighted average between $n_1$, $n_2$ and $n_3$ as soon as field is present in all these regions.

ZigZag waves model can still be applied with some care and $\theta_m$ can be assigned to each mode

# Possible range of the effective refractive index and maximum number of supported modes.

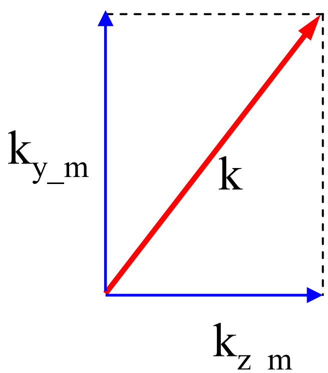
1. Perfect mirror case: zero field on the boundary between n-region and mirrors.




$$k^2 = \left(\frac{2\pi}{\lambda_0} n\right)^2 = k_{y\_m}^2 + k_{z\_m}^2, \quad k_{y\_m} = \frac{2\pi}{\lambda_{y\_m}} = \frac{2\pi}{2d} \cdot m = \frac{\pi}{d} \cdot m, \quad m = 1,2...$$

$$k_{y\_m} \le k, \quad \text{hence} \quad \frac{\pi}{d} \cdot m \le \frac{2\pi}{\lambda_0} n \quad \text{or} \quad \boxed{m \le \frac{d}{\lambda_0 / 2n}}$$

Effective refractive index can be found from:



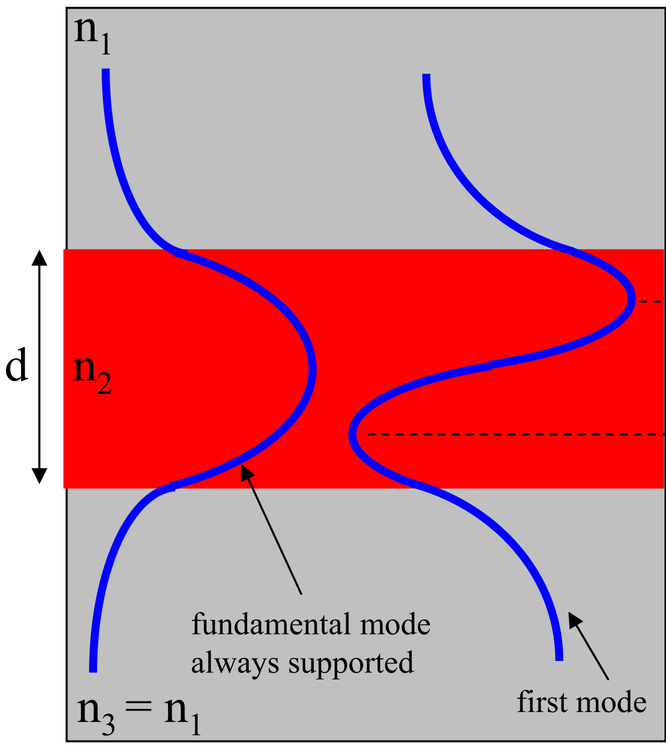

$$k^2 = \left(\frac{2\pi}{\lambda_0} \cdot n\right)^2 = k_{y\_m}^2 + k_{z\_m}^2 = \left(\frac{\pi}{d} \cdot m\right)^2 + \left(\frac{2\pi}{\lambda_0} \cdot n_{eff\_m}\right)^2$$

$$\boxed{n_{eff\_m}^2 = n^2 - \left(\frac{\lambda_0}{2} \cdot \frac{m}{d}\right)^2}$$

Maximum number of modes is equal to number of half waves that can be squeezed in d. Minimum $n_{eff}$ is zero and corresponds to extreme case when $k = k_y$ and no energy transfer occurs in z-direction – pure standing wave. Maximum $n_{eff} = n$, this corresponds to pure traveling wave when no mirrors present. When $d < \lambda_0/2n$ this waveguide supports no modes.

# Possible range of the effective refractive index and maximum number of supported modes.

2. <u>Semiconductor laser</u>: nonzero field in all layers $n_1$, $n_2$ and $n_3$.




For simplicity consider symmetric waveguide $n_1 = n_3$. In symmetric dielectric waveguide $n_{eff}$ can change between $n_1$ and $n_2$ because optical field penetrate into all regions. Actual value of $n_{eff\_m}$ can be found numerically

* before we plotted absolute value of the electric filed. Here we plot electric field with phase to assist the eye to recognize half wave distance between maximums.

The mode is guided if all maximums of the standing wave in y-direction are inside the confining region $n_2$. For the first mode (see figure) to exist waveguide width d should be larger than half wave in $n_2$ media to have standing wave maximums inside. For the second – larger than two half waves, for the third – three, etc.

In symmetric waveguide single lobe mode always exists and is called fundamental mode. Next mode exists if maximums of the field are inside $n_2$.

Number of supported modes m is given by:

$$m \le 1 + \frac{d}{\lambda_0 / 2n_2} \cdot \sqrt{1 - (n_1/n_2)^2}$$

Fundamental mode – always exists in symmetric waveguide

Important correction to perfect mirror case , see appendix for exact solution

# Single mode lasers.

Symmetric dielectric waveguide always supports at least one mode called fundamental mode.

*Asymmetric dielectric waveguide does not necessary supports this mode

For the waveguide not to support any other higher order modes the condition should be satisfied:

$$\boxed{d \cdot \sqrt{1-(n_1/n_2)^2} < \lambda_0 / 2n_2}$$

Single spatial mode operation of semiconductor laser produces current independent single lobe far field pattern. Single spatial mode operation lasers have the highest brightness.

Brightness **B** by definition is: $\boxed{B = \dfrac{P_\nu}{S \cdot \Omega}}$ , where S – emitting area, Ω – solid angle into which the power $P_\nu$ is emitted

Near field is spatial distribution of optical field across laser mirror, i.e. S.
Far field is angle distribution of the optical field far from laser mirror, i.e. Ω.

When laser emits single spatial mode S and Ω are related as Fourier transform pair and:

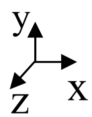
$$\boxed{S \cdot \Omega = \lambda^2, \quad \text{and brightness is maximum } Bmax = P_\nu / \lambda^2}$$

High brightness is desired in almost all applications.

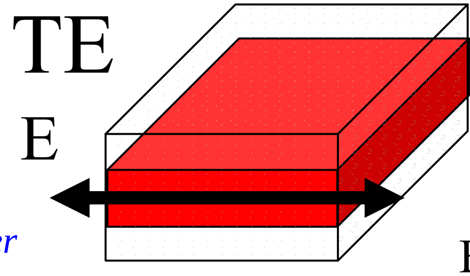
Single spatial mode operation is ideal operation condition of semiconductor laser.
Its advantages have to be sacrificed when high output power level is required.

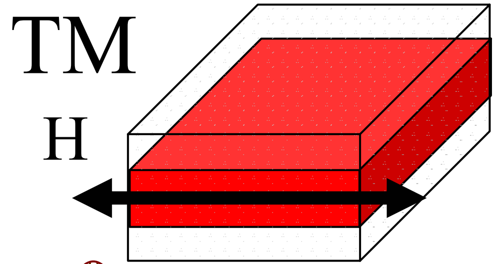
Usually, semiconductor laser are single mode in y-direction (transverse) and can have many spatial modes in x-direction (lateral).

# Transverse-electric (TE) and Transverse-magnetic (TM) modes.



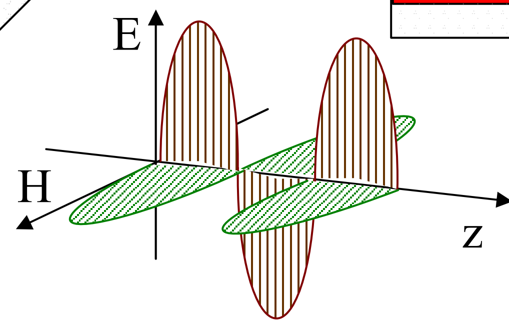

*light wave electric field component oscillates in the plane of active layer*



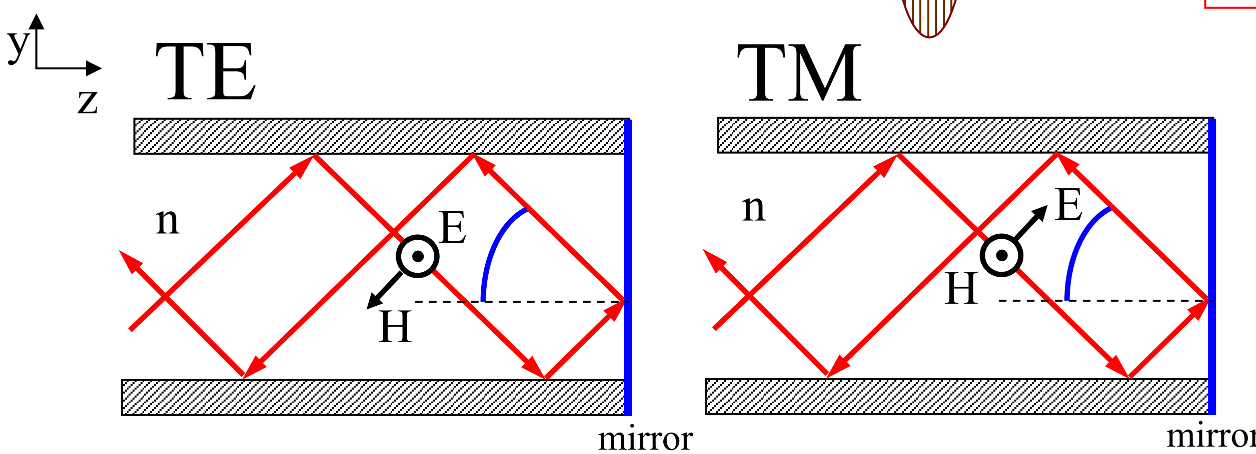




*light wave magnetic field component oscillates in the plane of active layer*

Electric and magnetic components of the light wave in isotropic media are orthogonal and are related by:

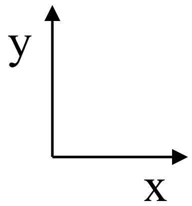



$$H = \sqrt{\frac{\varepsilon \cdot \varepsilon_0}{\mu \cdot \mu_0}} \cdot E = n \cdot \frac{E}{377}$$




TE and TM polarized light have different reflection coefficients at both waveguide boundaries and laser mirrors.

TE modes have lower mirror loss than TM modes and laser emission is usually TE polarized. In QW lasers mode gain for TE and TM polarization is also different.




# Lateral optical confinement (X-direction)

## Gain-guided

Oxide-Stripe

Current Confinement

Gain modifies Imε

I(x) leads to Imε(x)

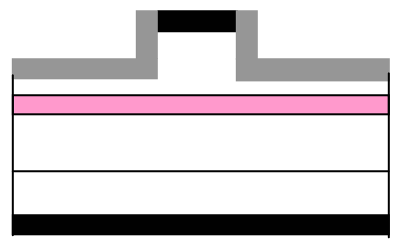
Multimode

Im index step ~ 0.001

**Dependent on pumping level*

**Antiguiding*

## Weakly Index-guided



Ridge

Current Confinement

Optical Confinement

Reε(x) & Imε(x)

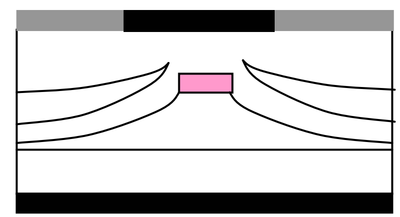
Single mode

*Refractive index step < 0.01*

**Antiguiding*

**Expensive*

## Strongly Index-guided



CMBH

Current Confinement

Optical Confinement

Reε(x)

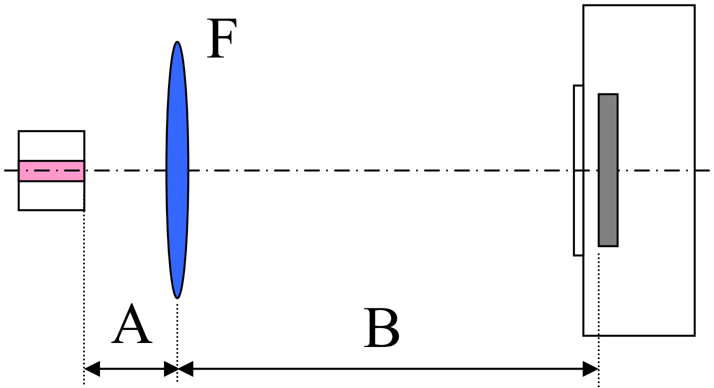
Stable single mode

*Refractive index step >0.1*

**Very expensive*

# Measurements of the laser near field

General approach is to amplify image of the laser output facet and project it on video camera.




$$\frac{1}{A} + \frac{1}{B} = \frac{1}{F}$$

$$M = B/A$$

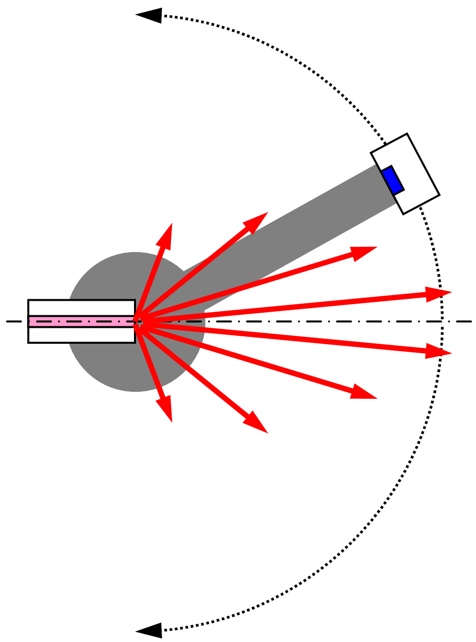
Magnification of 10-100 times or more is required for well resolved image

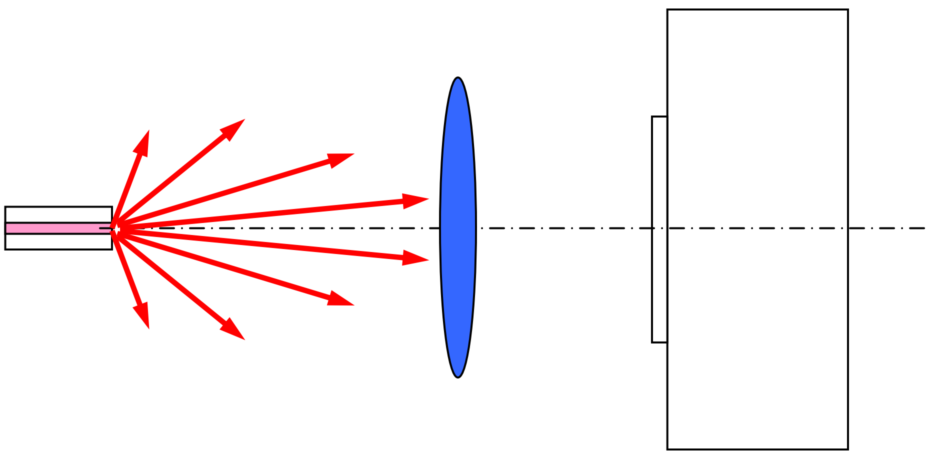
** Near field microscopy is another option: fiber tip is scanned with submicron resolution along laser output facet. This technique is accurate and free from aberrations that could be introduced by imaging optics.*

# Measurements of the laser far field

Scanning of the single detector

Detector array (CCD) or Vidicon camera





High resolution

true far field for all angles

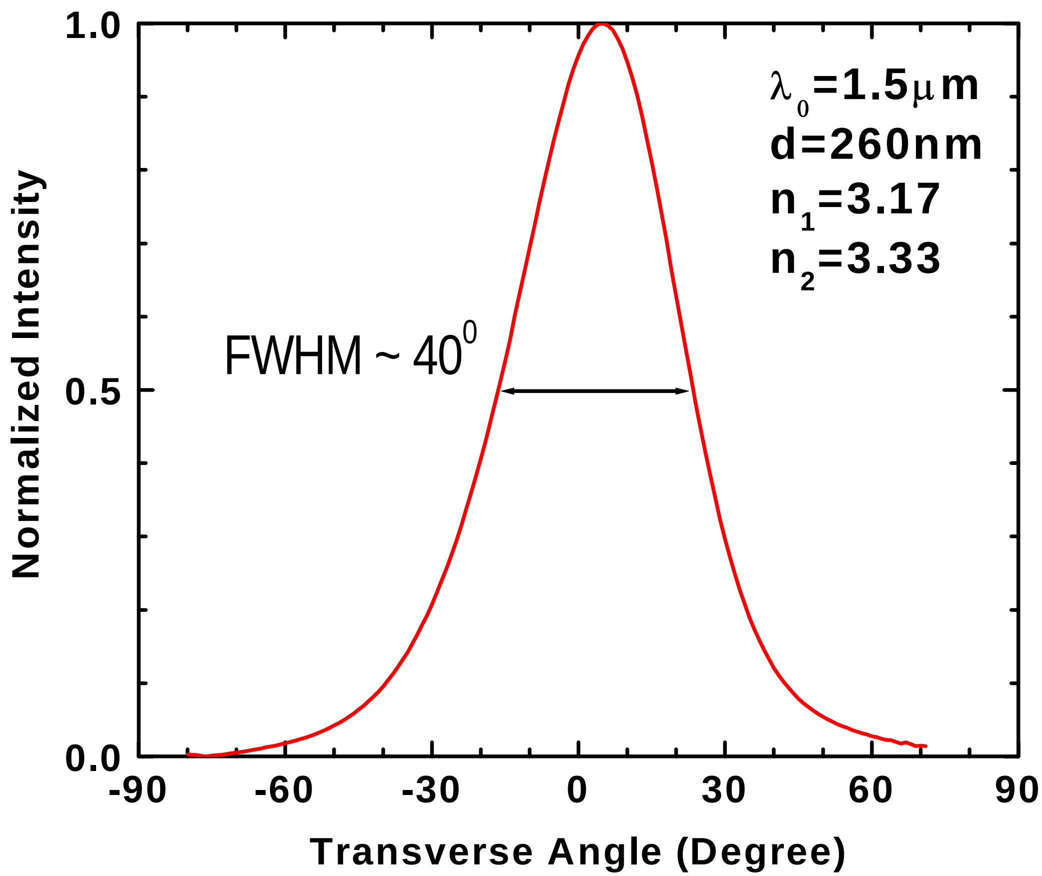
*Slow and only one dimension at a time*

Fast image of the 2D far field pattern

Easy alignment and adjustment

*Special optics required due to limited size of the photosensitive matrix*

# Typical diode laser transverse (Y) far field pattern



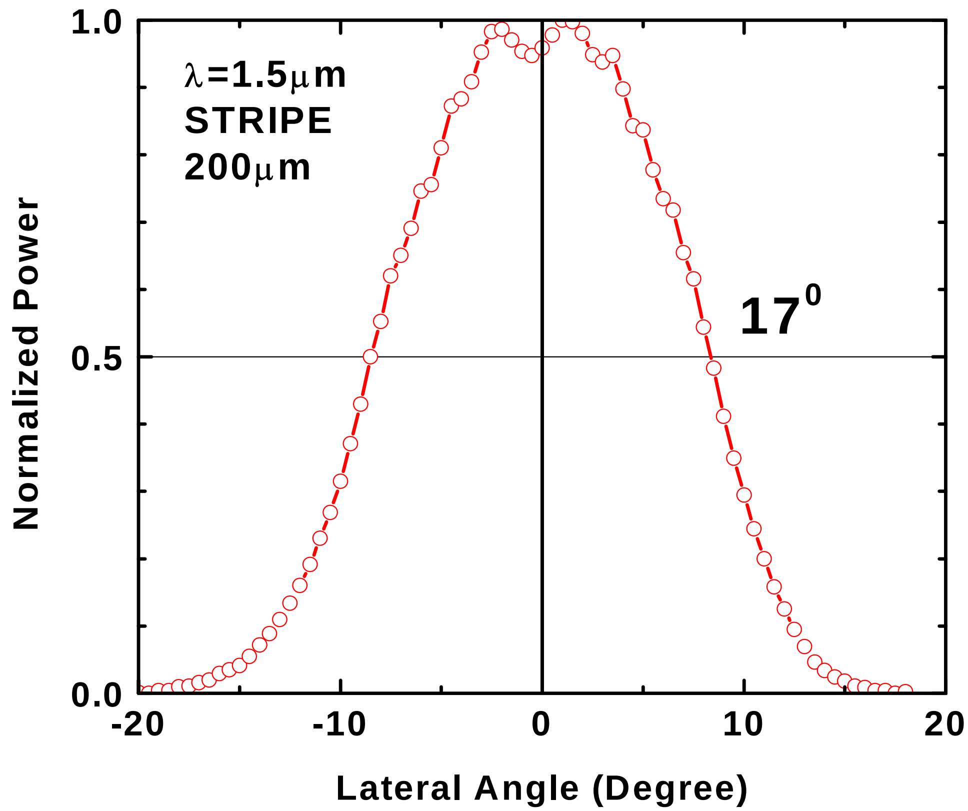

Approximate expression for full angle at half intensity for small d

$$\Theta_{\perp}(\mathrm{rad}) \approx 4 \cdot \left(n_2^2 - n_1^2\right) \cdot \frac{d}{\lambda_0}$$

Single mode operation (diffraction limited beam)

Beam divergence is current independent

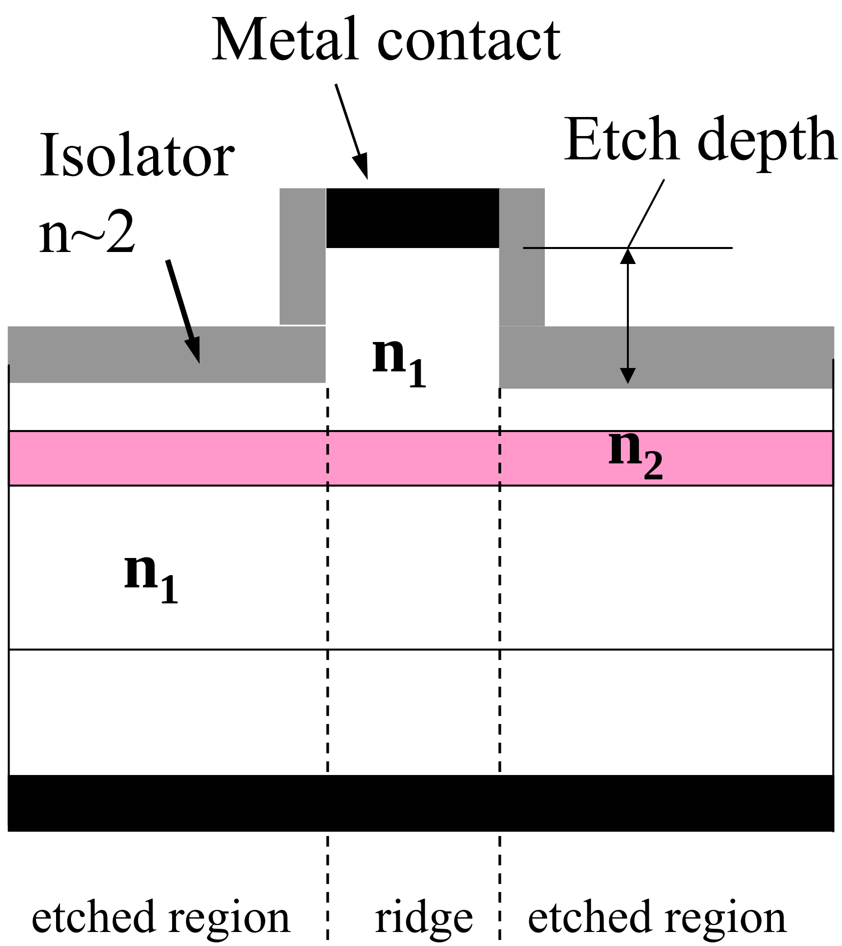
# Lateral (X) far field pattern of wide stripe (200µm) gain guided laser




Multimode operation

Beam divergence is current dependent and orders of magnitude higher than diffraction limited

# Ridge waveguide lasers and effective index technique




**1.** Find transverse effective indexes in ridge and etched sections, $n_{ridge}$ and $n_{etched}$

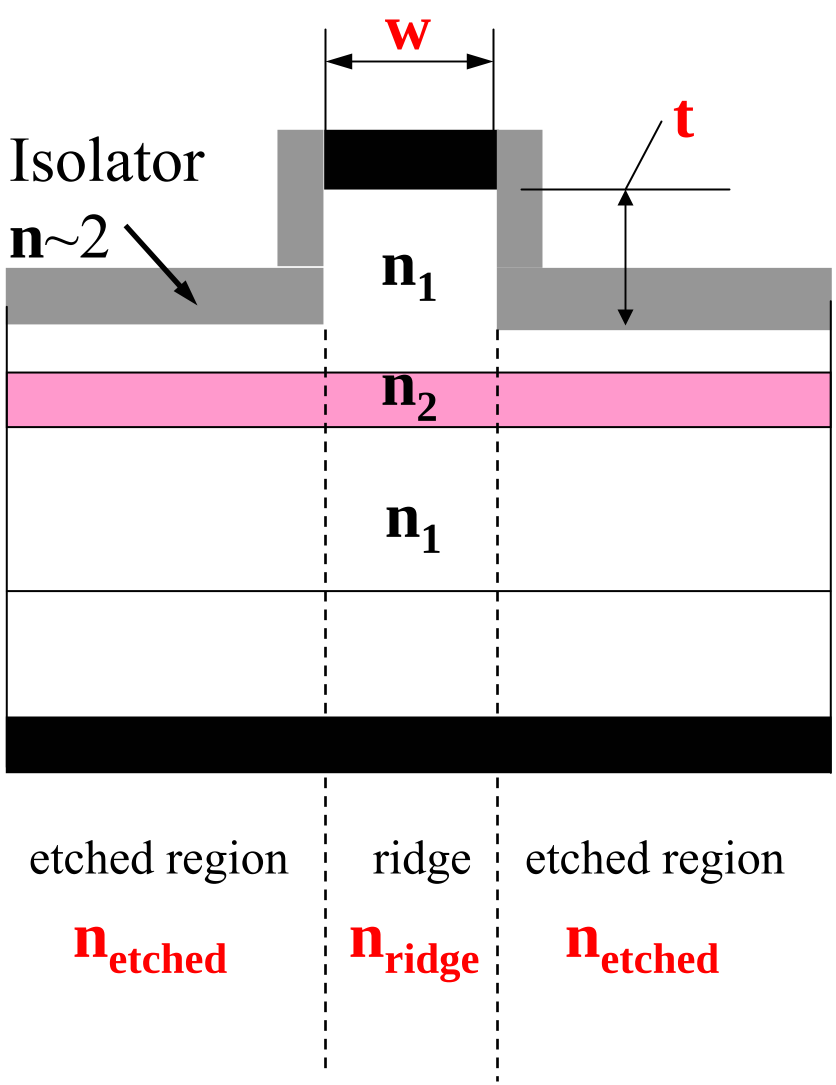
**2.** Use $n_{ridge}$ and $n_{etched}$ to find lateral field distribution with effective index $n_{lateral}$

3. Use $n_{ridge}$ for transverse near/far field calculations and $n_{lateral}$ for lateral near/far field calculations.

*Current spreading and gain guiding are usually important and should be taken into account.

* For CMBH devices lateral and transverse waveguide dimensions are comparable and exact 2D waveguide problem should be solved numerically.

# Design of single mode ridge waveguide laser




**Design parameters:**

**1. Ridge width – w**

**2. Etching depth - t**

**t** defines $\mathbf{n_{etched}}$ – transverse effective index of the etched region

$\mathbf{n_{ridge}}$ and $\mathbf{n_{etched}}$ define lateral effective index $n_{lateral}$

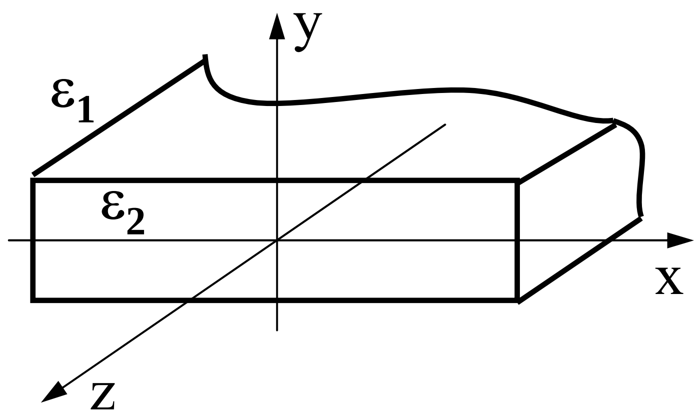
Lateral single mode condition

$$\boxed{w \cdot \sqrt{n_{ridge}^2 - n_{etched}^2(t)} < \frac{\lambda_0}{2}}$$

APPENDIX 1

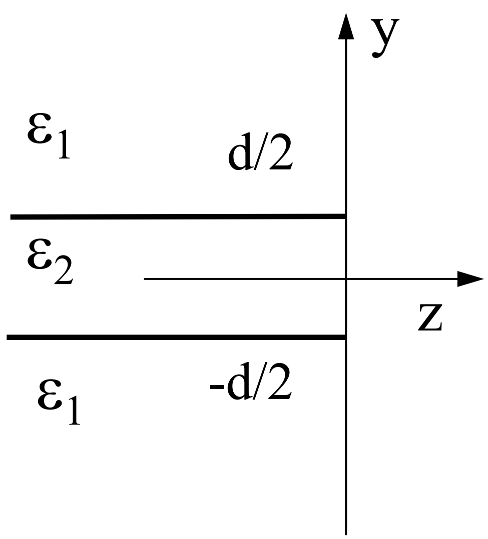


# Laser near field E(x,y)




$$\nabla^2 \vec{E}(\vec{r},t) = \mu_0 \varepsilon(\vec{r}) \cdot \frac{\partial^2 \vec{E}(\vec{r},t)}{\partial t^2}$$

## Consider TE modes in 3 layer symmetric waveguide




For TE modes $E_Z = E_Y = 0$ and d/dx=0

Let's look for the solution in the form

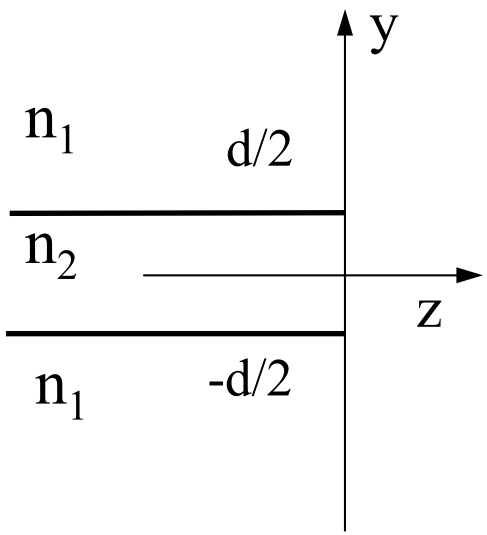
$$E_X(y,z,t) = E_0 \cdot E_X(y) \cdot \exp(j(\omega t - kz))$$

$$\left( \partial^2 E_X \middle/ \partial y^2 \right) + \left( \omega^2 \mu_0 \varepsilon - k^2 \right) \cdot E_X = 0$$

APPENDIX 1



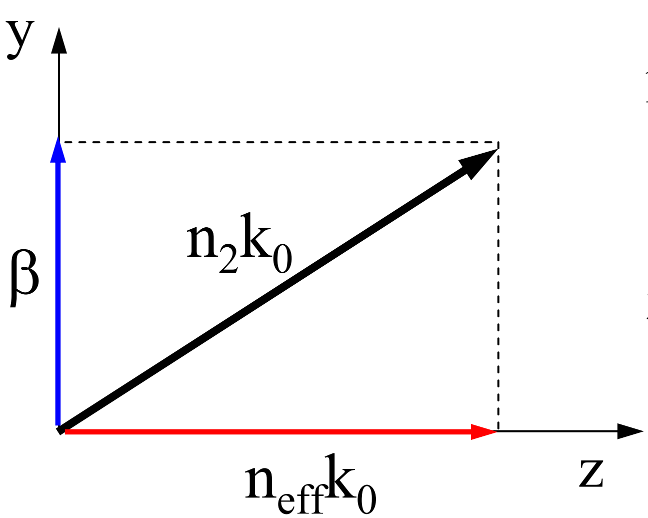
# Laser near field E(x,y)




$$\left(\frac{\partial^2 E_X}{\partial x^2}\right) + k_0^2\left(n_i^2 - n_{eff}^2\right)\cdot E_X = 0$$

$$k_0 = \frac{2\pi}{\lambda_0};\quad n_i^2 = \varepsilon_i;\quad n_{eff}^2 = \frac{k^2}{k_0^2}$$

# Solution for guided modes ($n_1 < n_{eff} < n_2$)




1. $-\frac{d}{2} < y < \frac{d}{2}$:

$$E_{X1}(y) = A_E\cos(\beta y) + A_O\sin(\beta y);\quad \beta^2 = \left(n_2^2 - n_{eff}^2\right)\cdot k_0^2$$

2. $y > \frac{d}{2}$: $E_{X2}(y) = B\exp(-\gamma y)$

$y < -\frac{d}{2}$; $E_{X3}(y) = C\exp(\gamma y)$; $\gamma^2 = \left(n_{eff}^2 - n_1^2\right)\cdot k_0^2$

APPENDIX 1



# Laser near field E(x,y)

Mode intensity distribution is defined by values of $A_E$, $A_O$, B, C and $n_{eff}$

They can be found from boundary and normalization conditions

1. Boundary condition:

Tangential components of the E and H should be continuous at the interfaces.

For TE modes it means:

$$E_{X1}\Big|_{d/2} = E_{X2}\Big|_{d/2} \quad \text{and} \quad \left.\frac{dE_{X1}}{dy}\right|_{d/2} = \left.\frac{dE_{X2}}{dy}\right|_{d/2}$$

$$E_{X1}\Big|_{-d/2} = E_{X3}\Big|_{-d/2} \quad \text{and} \quad \left.\frac{dE_{X1}}{dy}\right|_{-d/2} = \left.\frac{dE_{X3}}{dy}\right|_{-d/2}$$

2. Normalization condition:

Total area under the envelope curve should be equal to unity.

$$\int_{-\infty}^{\infty} E_X^2(y)\,dy = 1$$

# Laser near field E(x,y)

1. Observation of the boundary conditions obtains the equation:

Even TE modes ($A_O$=0): $$\frac{\beta d}{2}\cdot\tan\left(\frac{\beta d}{2}\right)=\frac{\gamma d}{2}$$

Odd TE modes ($A_E$=0): $$\frac{\beta d}{2}\cdot\cot\left(\frac{\beta d}{2}\right)=-\frac{\gamma d}{2}$$

2. Observation of the relation between k, γ and β gives:

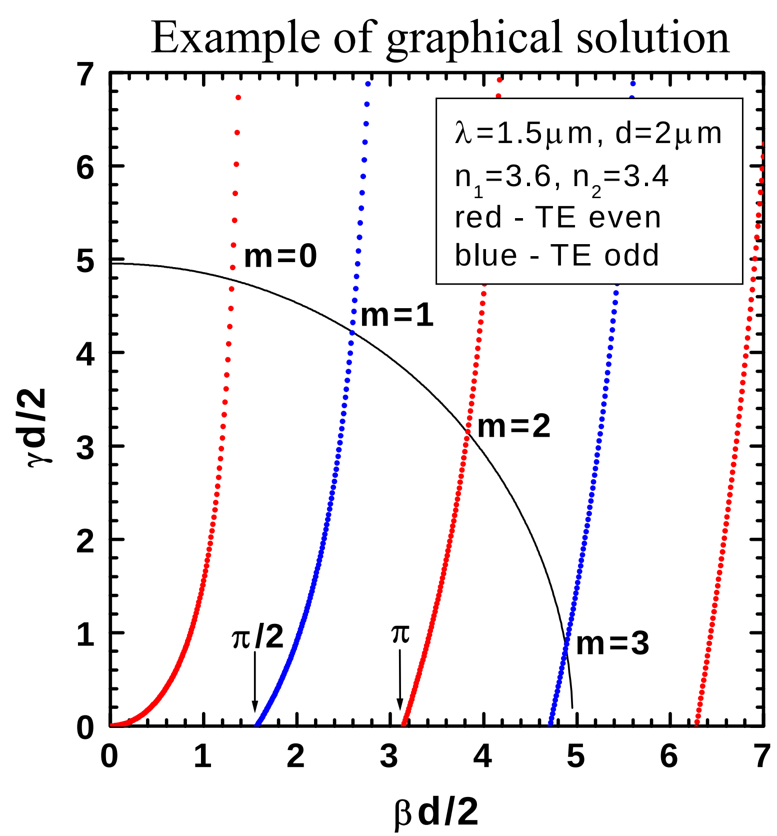
$$\left(\frac{d\beta}{2}\right)^2+\left(\frac{d\gamma}{2}\right)^2=\left(\frac{dk_0}{2}\right)^2\cdot\left(n_2^2-n_1^2\right)$$

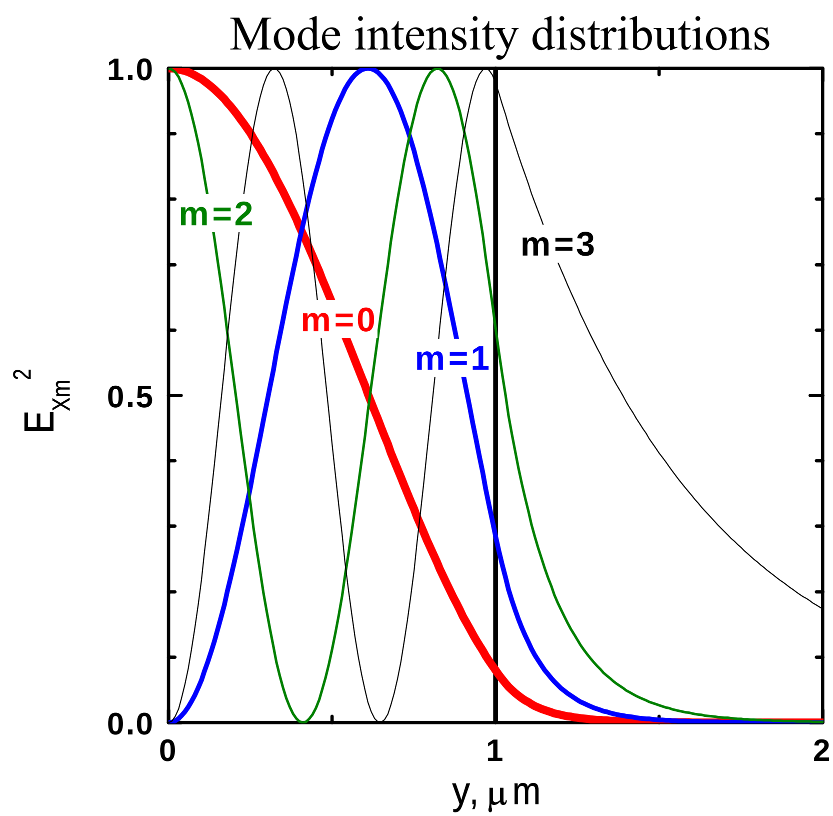
Numerical (graphical) solution of these equations gives discrete values of $n_{eff}$ for guided modes

APPENDIX 1



# Laser near field E(x,y)




Condition of the single mode operation: $d \cdot \sqrt{n_2^2 - n_1^2} < \frac{\lambda_0}{2}$

* In full analysis, mode loss and confinement should be taken into account