Integrated Arrayed Waveguide Grating Spectrometers for On-chip Optical Coherence Tomography and Raman Spectroscopy

B.Imran Akca, N. Ismail, F. Sun, A. Driessen, K. Wörhoff, M. Pollnau, and R.M. de Ridder

Integrated Optical Microsystems Group,
MESA+ Institute for Nanotechnology,
University of Twente,
Encshede,NL

V.Duc Nguyen, J. Kalkman, and T.G. van Leeuwen

Biomedical Engineering & Physics,
Academic Medical Center,
University of Amsterdam
Amsterdam,NL

Outline

- Guided Wave Optics
- Motivation
- Arrayed Waveguide Grating (AWG) Spectrometer Design for
  - On-chip Optical Coherence Tomography (OCT) Systems
  - Integrated Raman Spectroscopy
- Conclusions

Guided wave theory

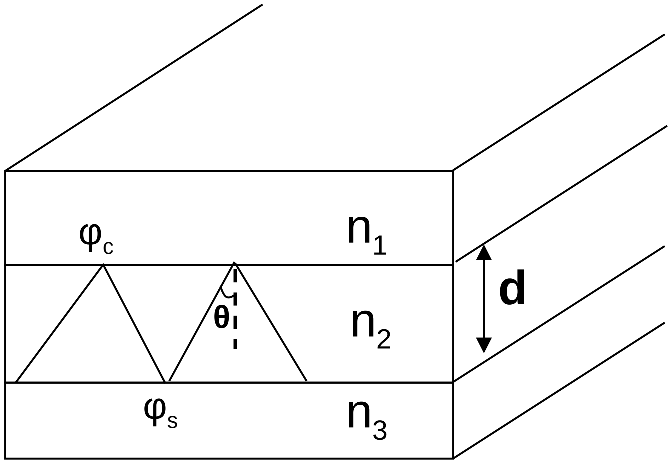
Optical waveguide: A physical structure for confining and guiding electromagnetic waves spatially.

→ Guiding mechanism: **total internal reflection (TIR)** $\theta < \cos^{-1}(n_2 / n_1)$

→ Wave guiding condition:

$$2dn_1k_0 \cos(\theta) - 2\varphi_s - 2\varphi_c = m2\pi \qquad (m = 0,1,2\ldots)$$

- m: mode number
- $k_0 d$ increase → number of modes increase



$n_2 > n_1,\ n_2 > n_3$

→ Longitudinal propagation constant:

$$\beta = k_0 n_2 \sin(\theta)$$

→ Effective refractive index:

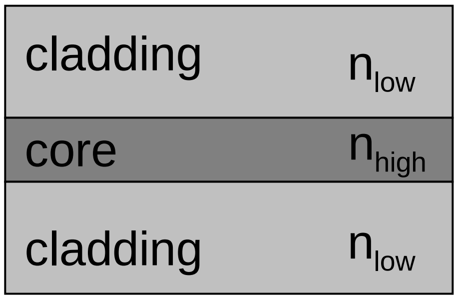
$$\beta / k_0 = n_2 \sin(\theta)$$

İmran Akça, b.i.akca@ewi.utwente.nl, IOMS Group

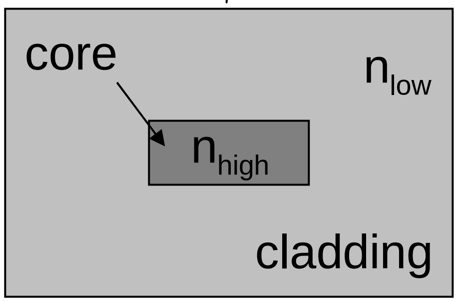
Waveguide geometries

1-d optical confinement

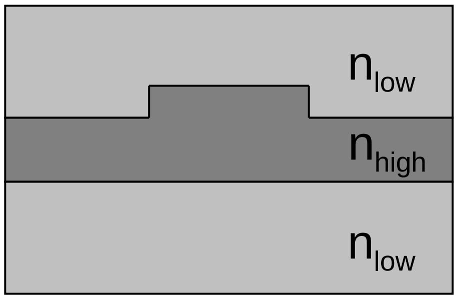
2-d optical confinement



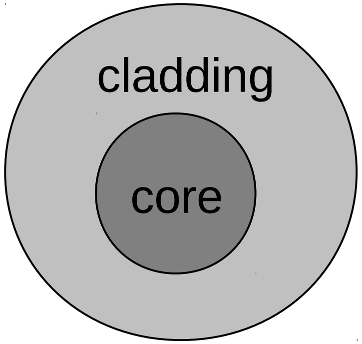
Slab waveguide



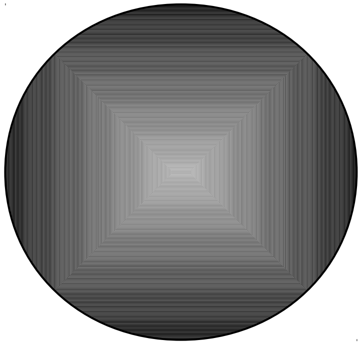
Channel/photonic wire waveguide



Rib/ridge waveguide



Step-index fiber



Graded-index (GRIN) fiber

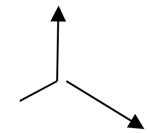
Wave approach to waveguides:

- One-dimensional planar waveguide: harmonic plane waves ($E(x,t) = A\cos[(kx - wt) - \theta]$)
- Rectangular waveguide: analytic solution does not exist
- Circular waveguide: Bessel functions
- Circular waveguide with parabolic *n*-profile: Gaussian beams ($E(r) = E_0 e^{-(r/w)^2}$)

1-d optical confined waveguide

$$\frac{\partial^2 E_\omega}{\partial x^2} + \omega^2 \mu_0 \epsilon E_\omega = 0$$

Helmholtz equation:



TE solutions:

$$\overline{E} = \hat{y}\, E_0\, U(x,y)\, e^{-j\beta z}$$

TM solutions:

$$\overline{H} = \hat{y}\, H_0\, U(x,y)\, e^{-j\beta z}$$

Solutions for TE

$$U_1 = B e^{\gamma x} \qquad \gamma^2 = \beta^2 - k_o^2 n_1^2$$ Decaying

$$U_2 = A \cos k_x x \qquad k_x^2 = k_o^2 n_2^2 - \beta^2$$ Propagating

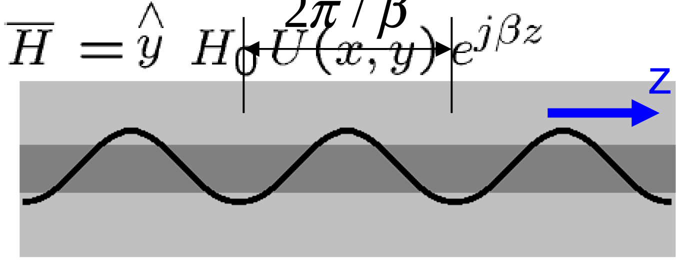
$$U_3 = B e^{-\gamma x} \qquad \gamma^2 = \beta^2 - k_o^2 n_3^2$$ Decaying

olutions:

$$\overline{E} = \hat{y}\, E_0\, U(x,y)\, e^{-j\beta z}$$

olutions:

$$\overline{H} = \hat{y}\, H_0\, U(x,y)\, e^{-j\beta z}$$



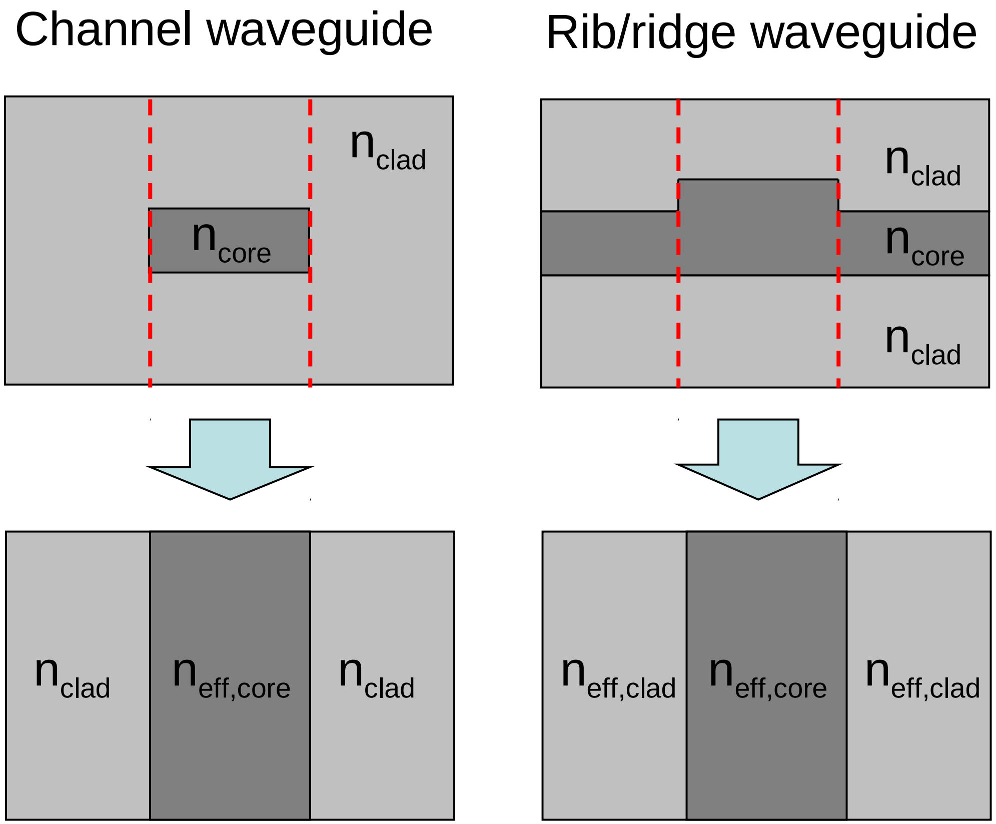
Propagation constant is related to the wavelength (spatial periodicity) of light propagating in the waveguide

effective index

$k = nk_0 = n2\pi/\lambda$ Propagation constant: $\beta = n_{eff}\, k_0$

Confinement in one direction → Little practical application

2-d confinement & effective index method

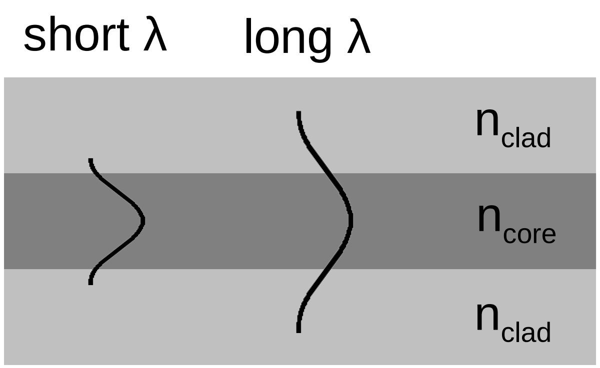


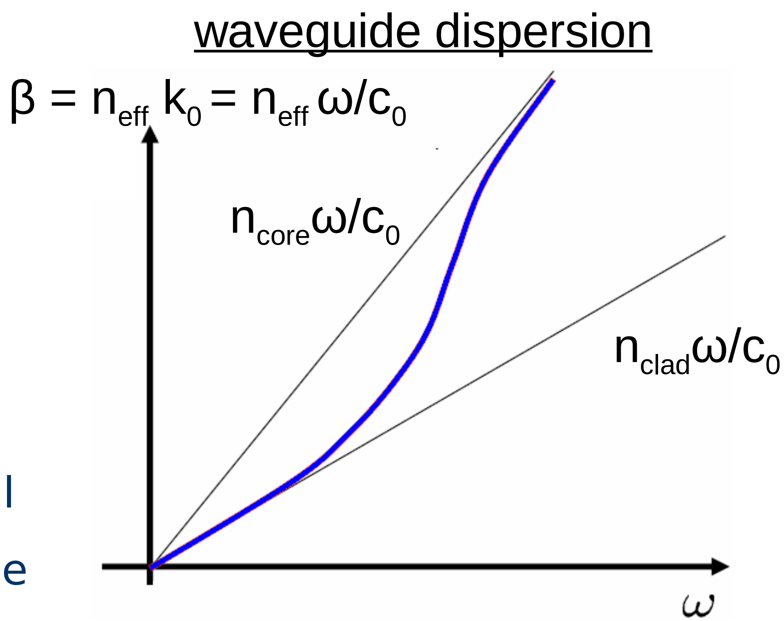
- Directly solving 2-d Helmholtz equation for U(x,y)
- Deconvoluting the 2-d equation into two 1-d problems
  - Separation of variables
  - Solve for U'(x) & U"(y)
  - U(x,y) ~ U'(x) U"(y)
- Less accurate for high-index-contrast waveguide systems
- Computationally very efficient

TM (TE) Equations → **TE (TM) Equations** → **$n^{TM(TE)}$**

Dispersion: The Basics

- In optics, **dispersion** is the phenomenon in which the phase /group velocity of a wave depends on its frequency.
- Dispersion is a measure of the seperation between diffracted ligth of different wavelengths.
- Caused by Sources, Waveguide Geometry, Materials, Differences in Mode Propagation





- At long wavelength, effective index is small
- At short wavelength, effective index is large

Dispersion:Types

- **Modal dispersion:**

  In multimode waveguides as a result of the differences in the group velocities of the various modes

- **Waveguide dispersion**

  Propagation constant depends on the wavelength even for single mode waveguides

- **Material dispersion:**

  The wavelength dependence of a material's refractive index

  (i.e. the separation of colors in a prism)

Other aspects of Waveguides

- **Single mode operation**

  The number of confined modes, and the shape of modes are a function of:

  - **Δn (core/ cladding)**
  - Waveguide **dimensions (height for slab waveguide)**
  - Operation **wavelength**

- **Low Loss**
  - Essential for all optical waveguides.
  - Mostly,fabrication dependent (impurities, roughness)
  - Scattering losses due to sidewall roughness is significant.
  - Bending losses.

- **Low birefringence**

  $\Delta n = n_{te} - n_{tm}$

  - Important for devices which needs to be polarization insensitive.