Computations for the Design of an Integrated Surface Acoustic Wave (SAW) Controlled Semiconductor Optical Source

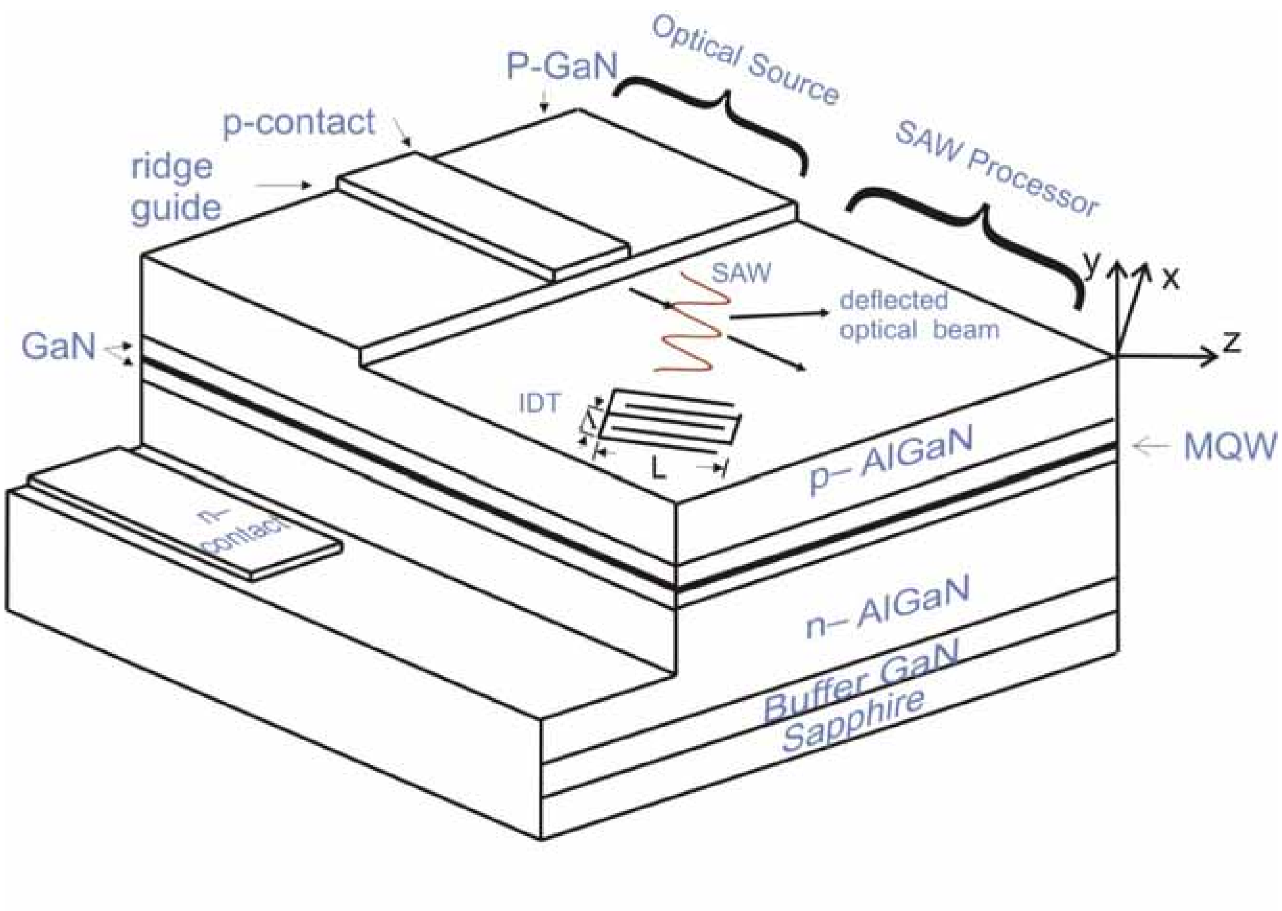
Q. Meng, F. Causa, J Sarma

Department of Electronic and Electrical Engineering

University of Bath, UK

Content

SAW Integrated Semiconductor Optical Source



- Acousto-optic effect

$\Delta\varepsilon \propto$ Acoustic Intensity

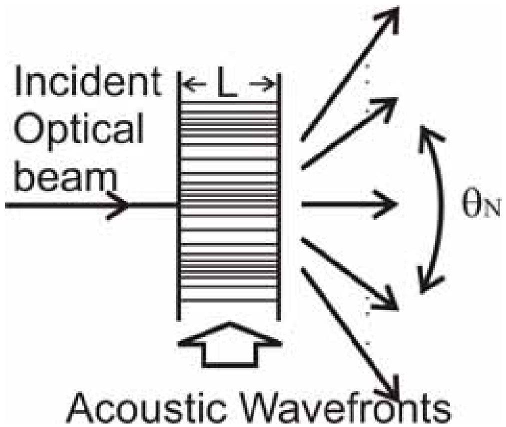
Acoustic Λ of f~1GHz
~ Optical λ

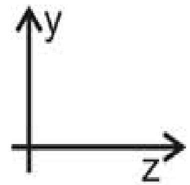
- Multilayer structure

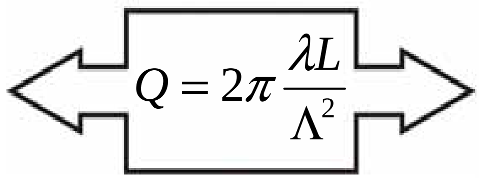
- Material: GaN

Acousto-Optic (AO) Effect

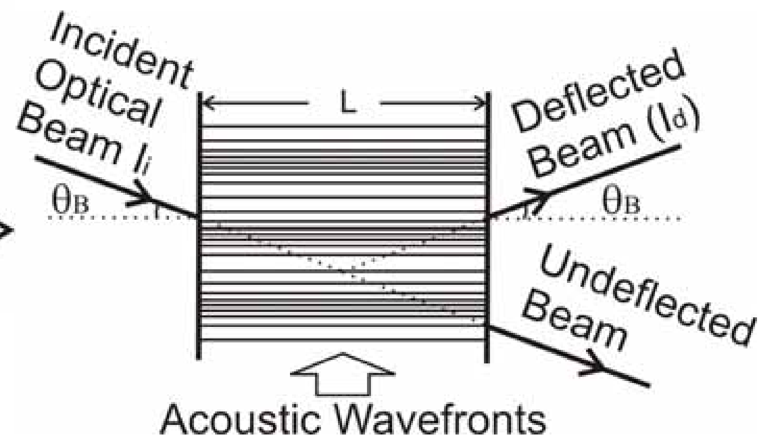
Raman-Nath Regime







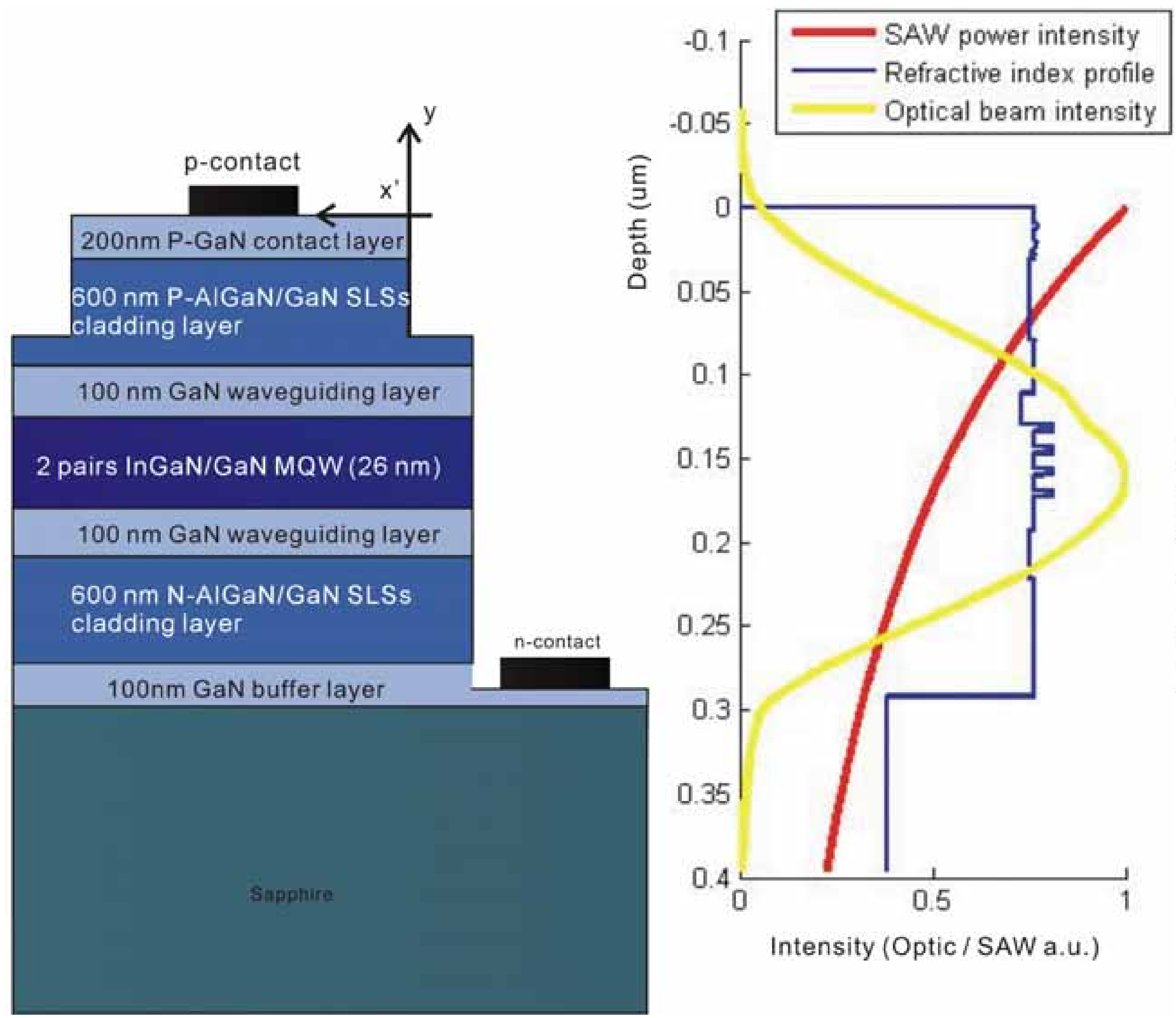
Bragg Regime



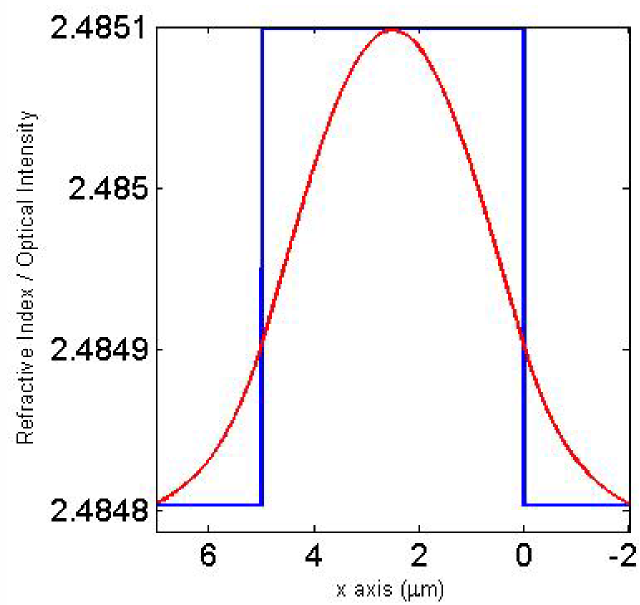
- Phase grating
- Normal incidence
- Multi-diffracted-beams
- Q < 2π

- Thick grating
- Oblique incidence
- Single diffracted beam
- Q > 4π
- Bragg angle $\theta_B = \frac{\lambda}{2n\Lambda}$

Optical Source: Laser/SLED

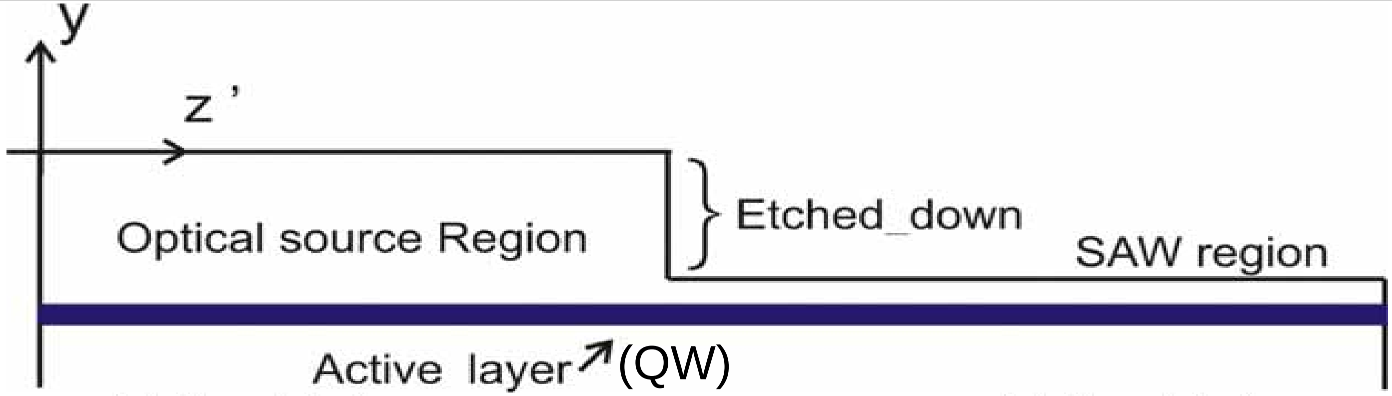


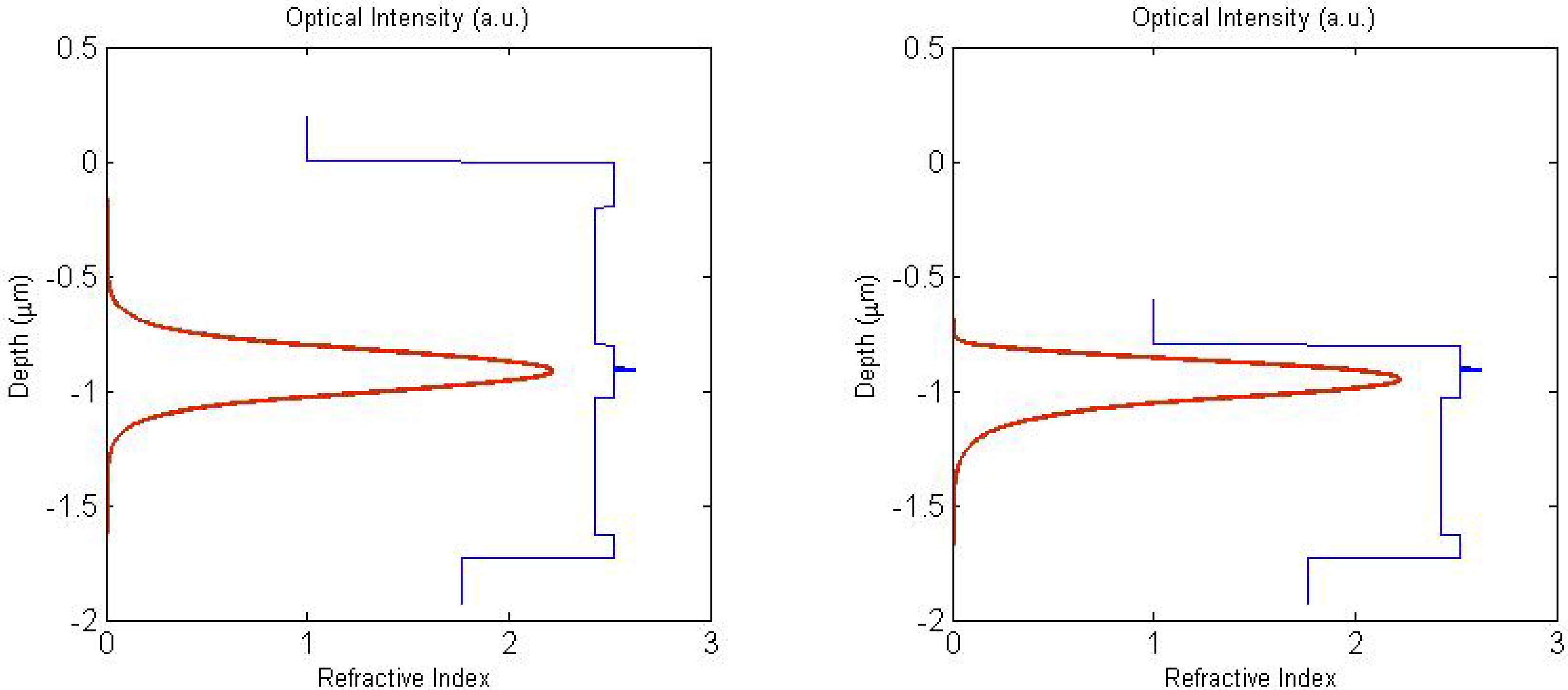
Optical Mode in Ridge Waveguide



Blue: Refractive Index
Red: Optical mode

Optical Mode Profiles

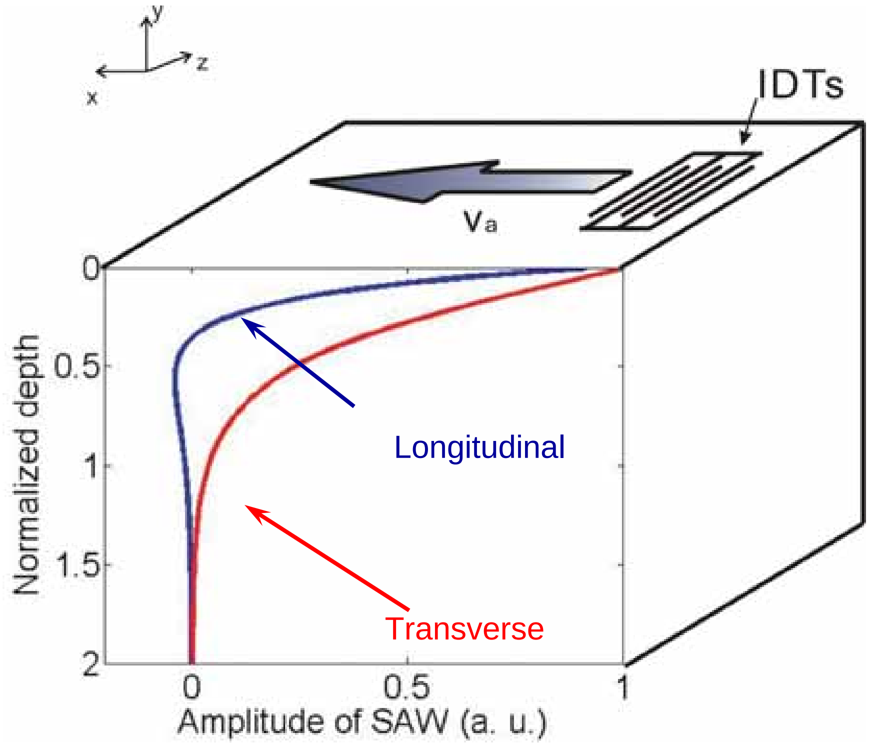




Surface Acoustic Wave (SAW)

SAW Advantages

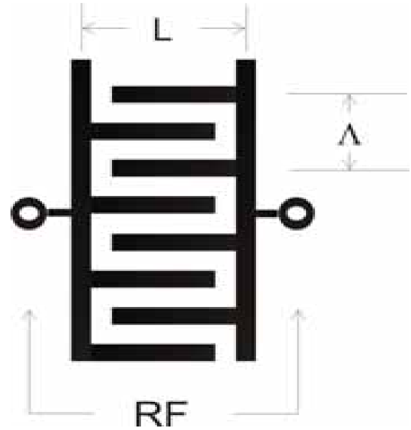
- Convenient integration
- Effective AO interaction



SAW distribution along y axis

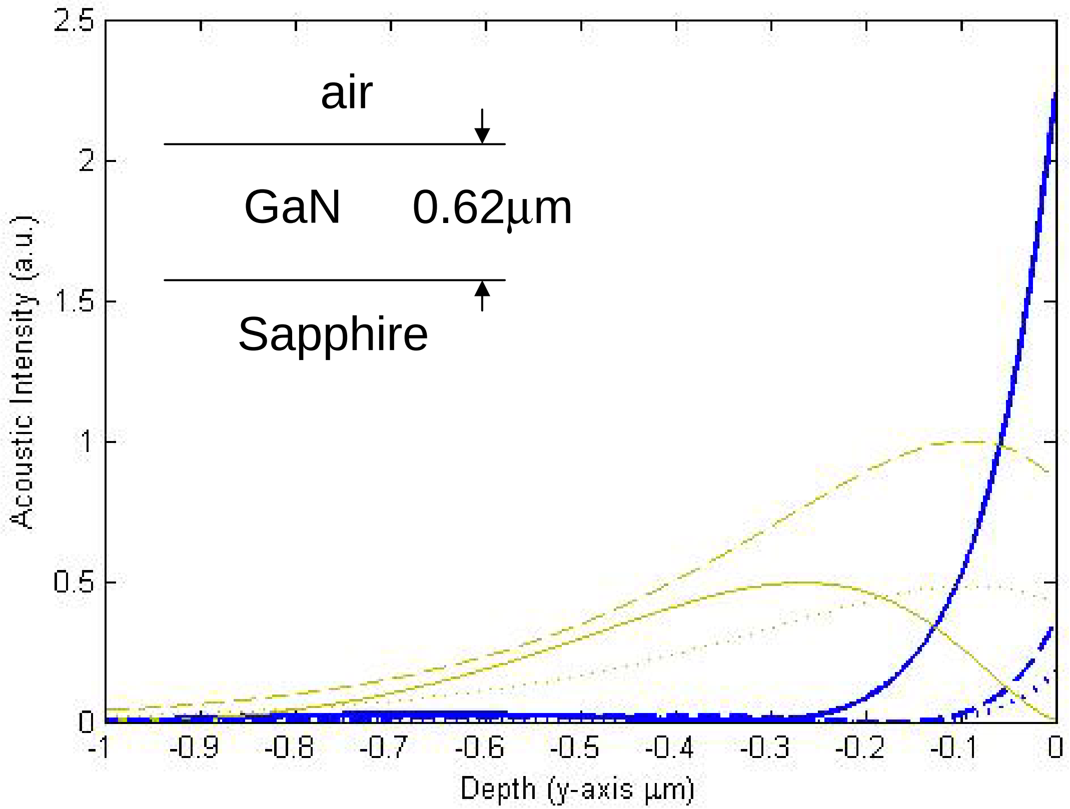
SAW Excitation

- Piezoelectric effect
  Electric field ↔ Strain
- Interdigital transducers (IDTs)



V_a = SAW velocity
($\propto$ propagation const.)
Λ = SAW wavelength
y/Λ = Nomalized depth

Acoustic Mode Profile - multilayer



Blue curves: Longitudinal wave
Yellow curves: Transverse wave
Solid: three layer approximation
Dashed: air/GaN semi-infinite
Dotted: air/Sapphire semi-infinite

- Acoustic wave equation (Longitudinal)

$$\rho \frac{\partial^2 u_x}{\partial t^2} = c \frac{\partial^2 u_x}{\partial x^2}$$

ρ, mass density, c, elastic index

- Particle displacements

$$\mathbf{u}_l = \mathbf{A} e^{-j(\beta_a x + L y)}$$

$$\mathbf{u}_t = \mathbf{B} e^{-j(\beta_a x + T y)}$$

- Dispersion relationship

$$\beta_a^2 + L^2 = \Omega^2 / v_l^2$$

$$\beta_a^2 + T^2 = \Omega^2 / v_t^2$$

Ω, acoustic angular frequency

GaN: Vl = 8000m/s Vt = 4130m/s

Sapphire: Vl = 11215m/s Vt = 5983m/s

Simplification of EM Solution: Effective Dielectric C

- Optical wave equation in grating

$$[\partial_x^2 + \partial_y^2 + \partial_z^2 + k_0^2 \epsilon(x, y)]E(x, y, z) = 0$$

- EDC approximation

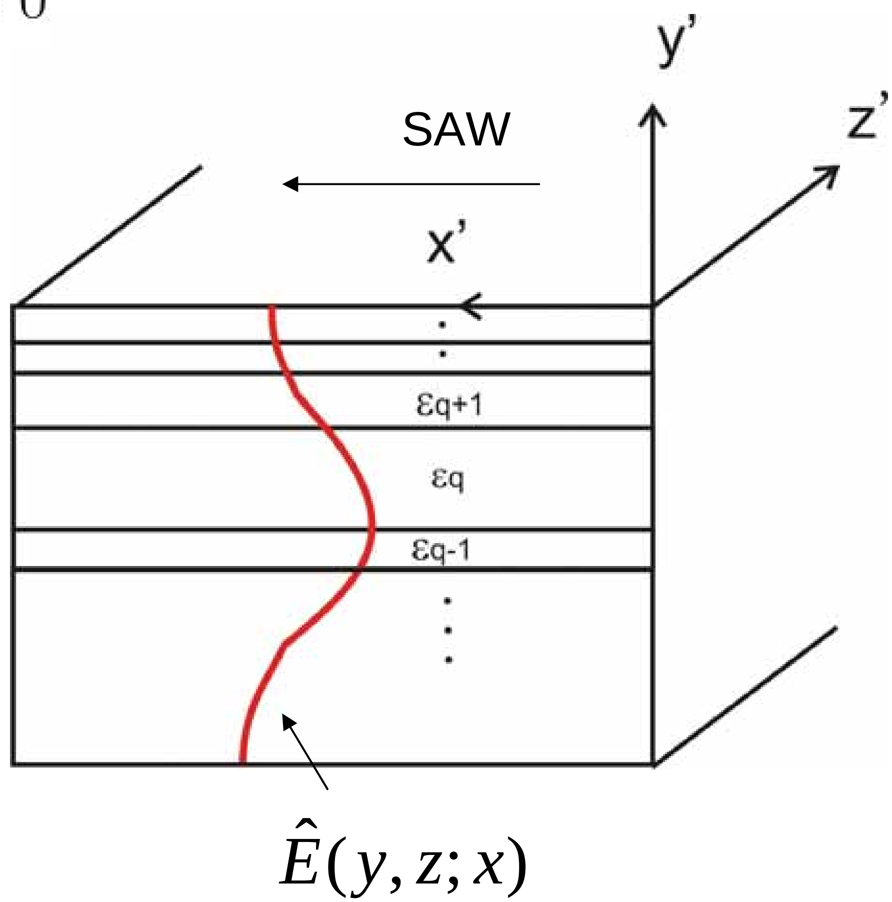
$$[\partial_y^2 + \partial_z^2 + k_0^2 \varepsilon(y; x)]\hat{E}(y, z; x) = 0$$

$$\hat{E}(y, z; x) = \Psi(y; x) e^{-j\beta(x) z}$$

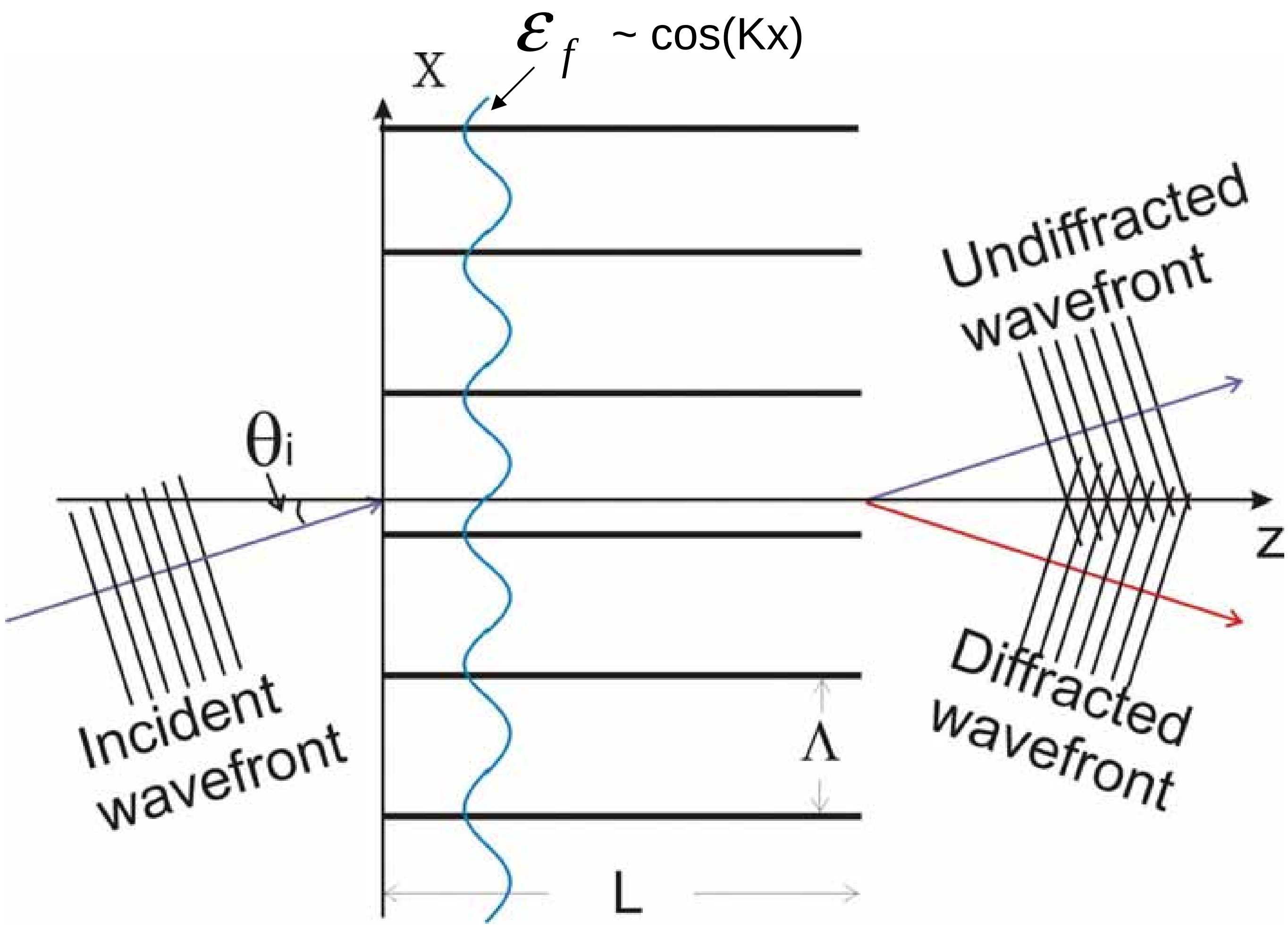
$$\varepsilon_f(x) = \left(\frac{\beta(x)}{k_0}\right)^2$$

$$[\partial_x^2 + \partial_z^2 + k_0^2 \varepsilon_f(x)]\tilde{E}(x, z) = 0$$

$$E(x, y, z) = \Psi(y; x)\tilde{E}(x, z)$$



Schematic of Plane Wave Diffraction



Diffraction Analysis: Coupled Wave Theory

- Optical wave equation in grating

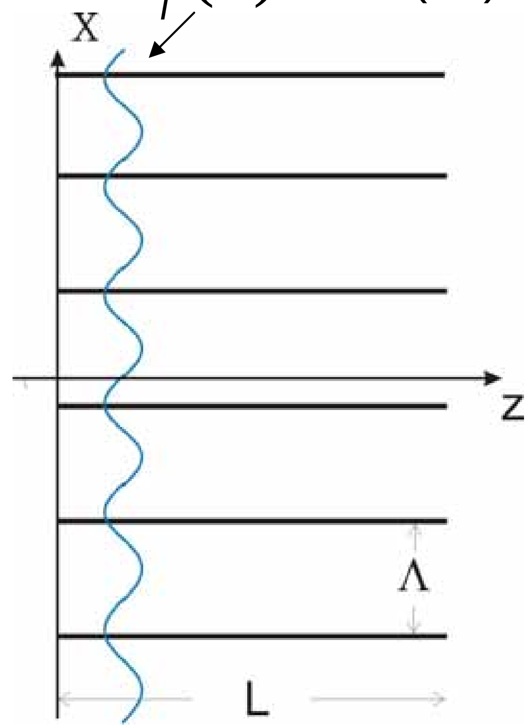
$$[\partial_x^2 + \partial_z^2 + k_0^2 \epsilon_f(x)]E(x,z) = 0$$

- Using Floquet-Bloch Theory

ε_f with periodicity Λ

$$E(x,z) = \sum_{m=-\infty}^{\infty} U_m(z) e^{-j(\beta_0 + mK)x} e^{-jk_z z}$$

Where $\beta_0^2 + k_z^2 = \bar{\epsilon}_f k_0^2$ and $K = 2\pi / \Lambda$



- $\epsilon_f(x) = \bar{\epsilon}_f + \Delta\epsilon_f \cos(Kx)$

For this special case obtain,

$$\frac{d^2 U_m(z)}{dz^2} - 2jk_z \frac{dU_m(z)}{dz} + \frac{1}{2} k_0^2 \Delta\epsilon_f (U_{m-1} + U_{m+1}) - (m^2 K^2 + 2m\beta_0 K) U_m = 0$$

Approximated Coupled Wave Theory

- only m $= 0$ and m $= -1$ used - since $\theta_i \approx \theta_B$
- 2^{nd} derivative ignored - since $\Delta\varepsilon_f$ is small

$$\frac{dU_0(z)}{dz} = -j\kappa U_{-1}(z)$$
$$\frac{dU_{-1}(z)}{dz} - j\gamma U_{-1} = -j\kappa U_0(z)$$

$$\kappa = \frac{k_0^2 \Delta\epsilon_f}{4k_z} \qquad \gamma = \frac{K^2 - 2\beta_0 K}{2k_z}$$

$$\gamma_- = \frac{\gamma}{2} - \sqrt{(\frac{\gamma}{2})^2 + \kappa^2} \qquad \gamma_+ = \frac{\gamma}{2} + \sqrt{(\frac{\gamma}{2})^2 + \kappa^2}$$

- Diffraction efficiency : Power ratio of Diffracted to Incident wave

$$\eta = \frac{4\kappa^2\gamma_+^2}{(\kappa^2 + \gamma_+^2)^2} \sin^2(\sqrt{(\gamma/2)^2 + \kappa^2} z)$$

- For $\theta_i = \theta_B$, i. e. $\gamma = 0$

$$\eta = \sin^2(\kappa z)$$

Diffraction Analysis: Modal theory

- Optical wave equation in the grating

$$[\partial_x^2 + \partial_z^2 + k_0^2\epsilon_f(x)]E(x,z) = 0$$

- Modal Expansion

$$E(x,z) = \sum_{p=-\infty}^{\infty} A_p \Phi_p(x) e^{-j(\beta_0 x + \xi_p z)}$$

- Using Floquet-Bloch Theory for εf with general periodicity of Λ

$$\Phi_p(x) = \sum_{m=-\infty}^{\infty} a_{mp} e^{-jmKx}$$

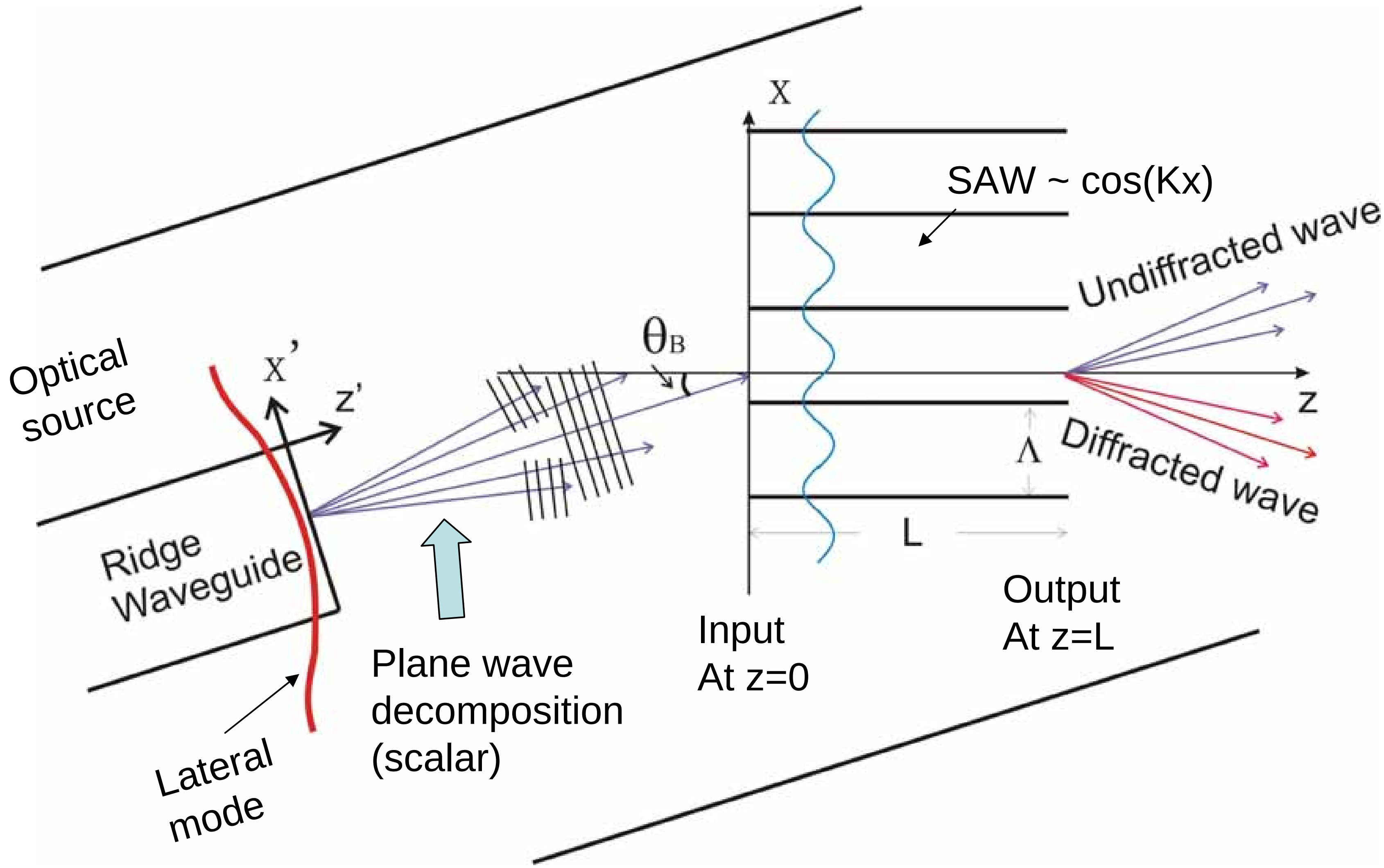
Where ξ_p is the *p*th modal propagation constant

- $\epsilon_f(x) = \bar{\epsilon}_f + \Delta\epsilon_f \cos(Kx)$

For this special case obtain,

$$\frac{1}{2}\Delta\epsilon_f \omega^2 \mu a_{(m-1)p} + (\omega^2\mu\epsilon_0 - (\beta 0 + mK)^2)a_{mp} + \frac{1}{2}\Delta\epsilon_f \omega^2 \mu a_{(m+1)p} = \xi_p^2 a_{mp}$$

Integration Design



Typical Integrated Device Parameters

Optical parameters

Material: GaN on Sapphire
Optical λ in vacuum: 405nm
$\bar{\varepsilon}_f$ in SAW region ~ 6.1
$\Delta\varepsilon_f$ due to SAW ~ 0.01
Ridge width: ~ 2μm

AO parameters

AO diffraction regime: Bragg diffraction
Q: 50.6π >> 4π (at L = 4μm)
θ_B: 1.2 degree (at L = 4μm)
η: 100% (at z=L= 4μm, Pa=180 mW)

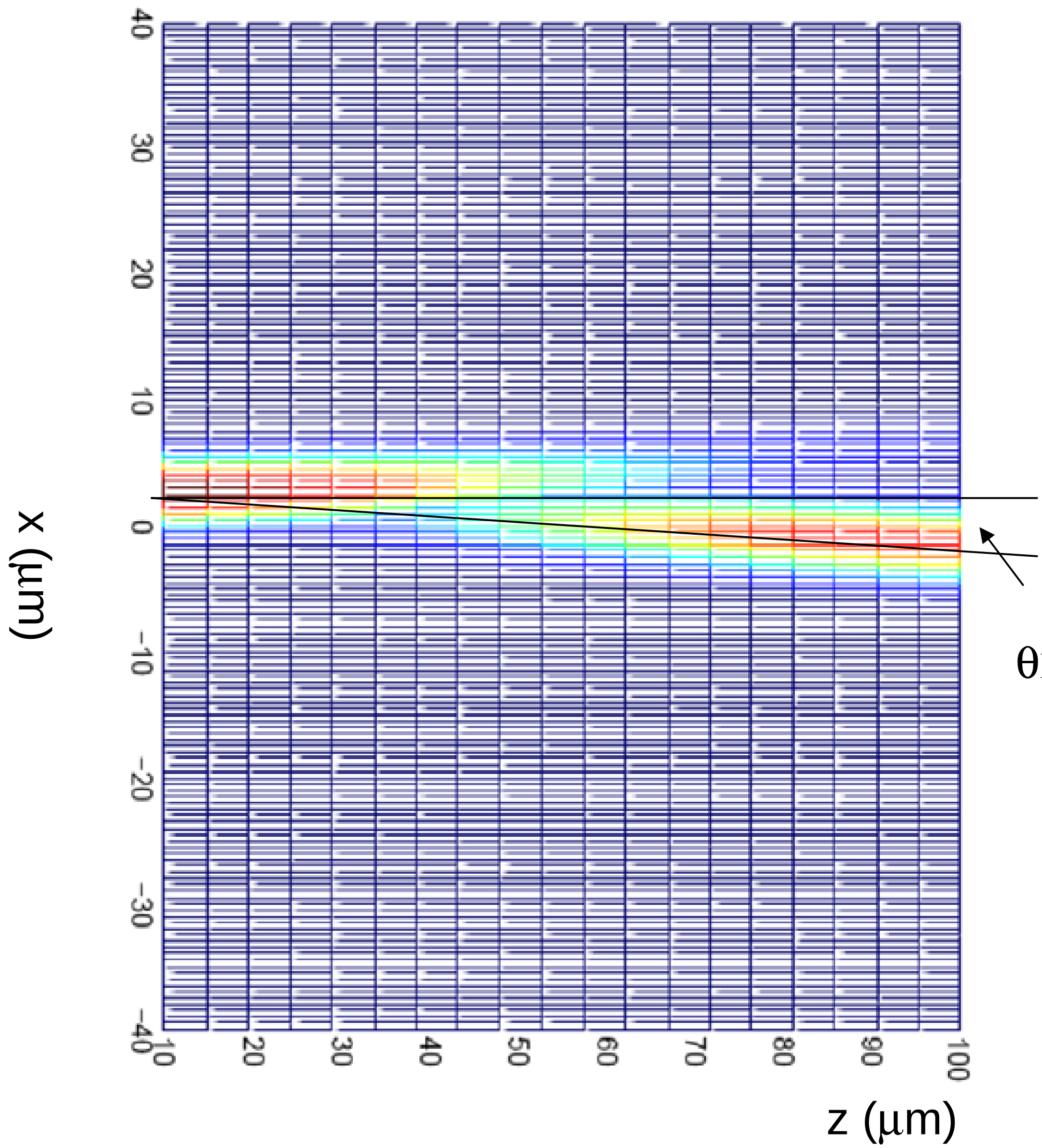
SAW parameters

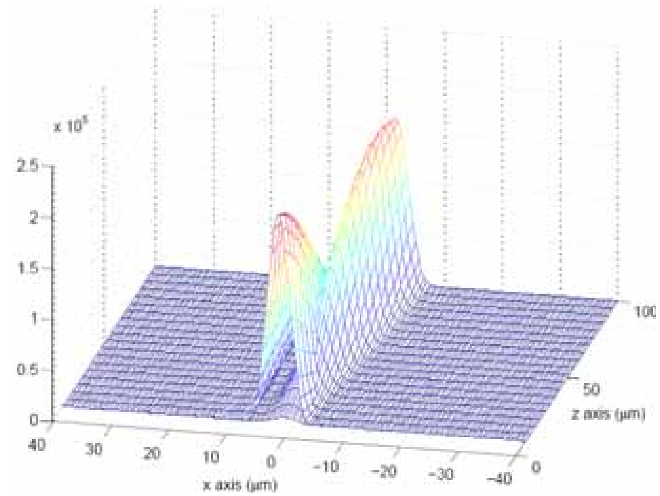
SAW Λ: 4μm
SAW velocity: 4000m/s
SAW f : 1GHz
SAW Width L: 100μm

IDT parameters

IDT f : 1GHz
IDT power: 180mW

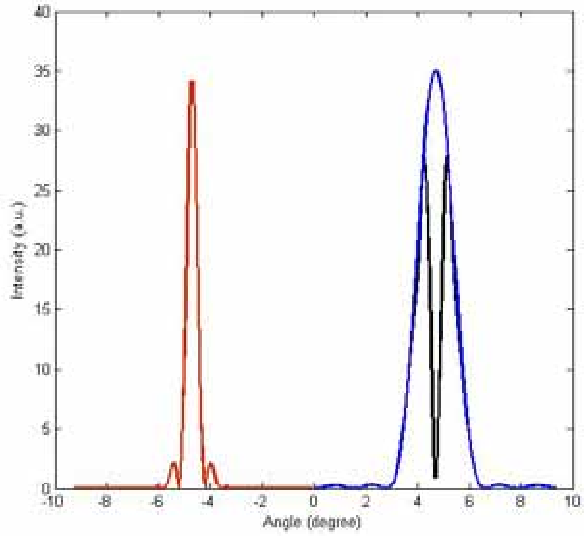
Optical field profile along grating



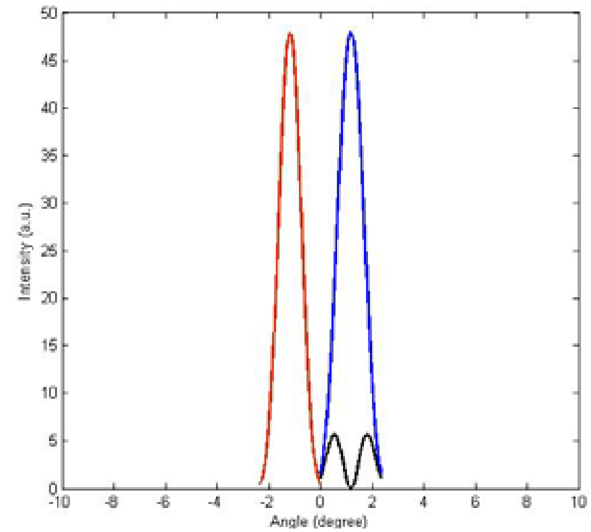


θ_B: 1.17 degree

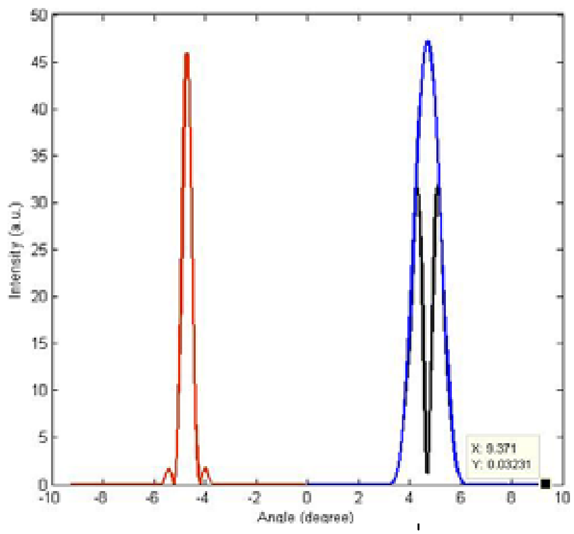
Input and Output Angular Distributions



Ridge width: 2µm Λ: 1µm

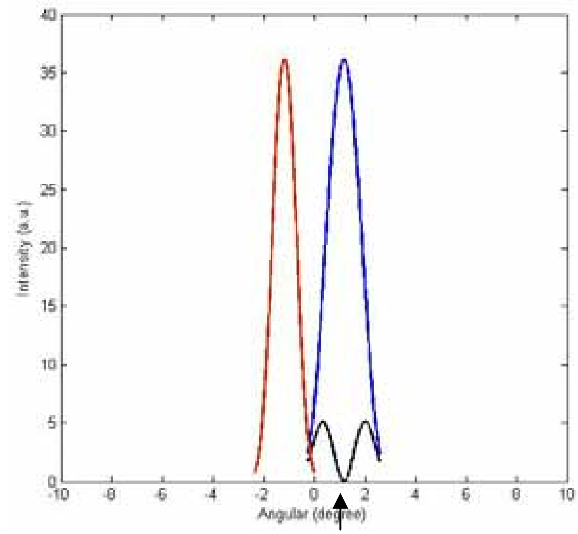


Ridge width: 2µm Λ: 4µm



Ridge width: 5µm Λ: 1µm

Bragg angle

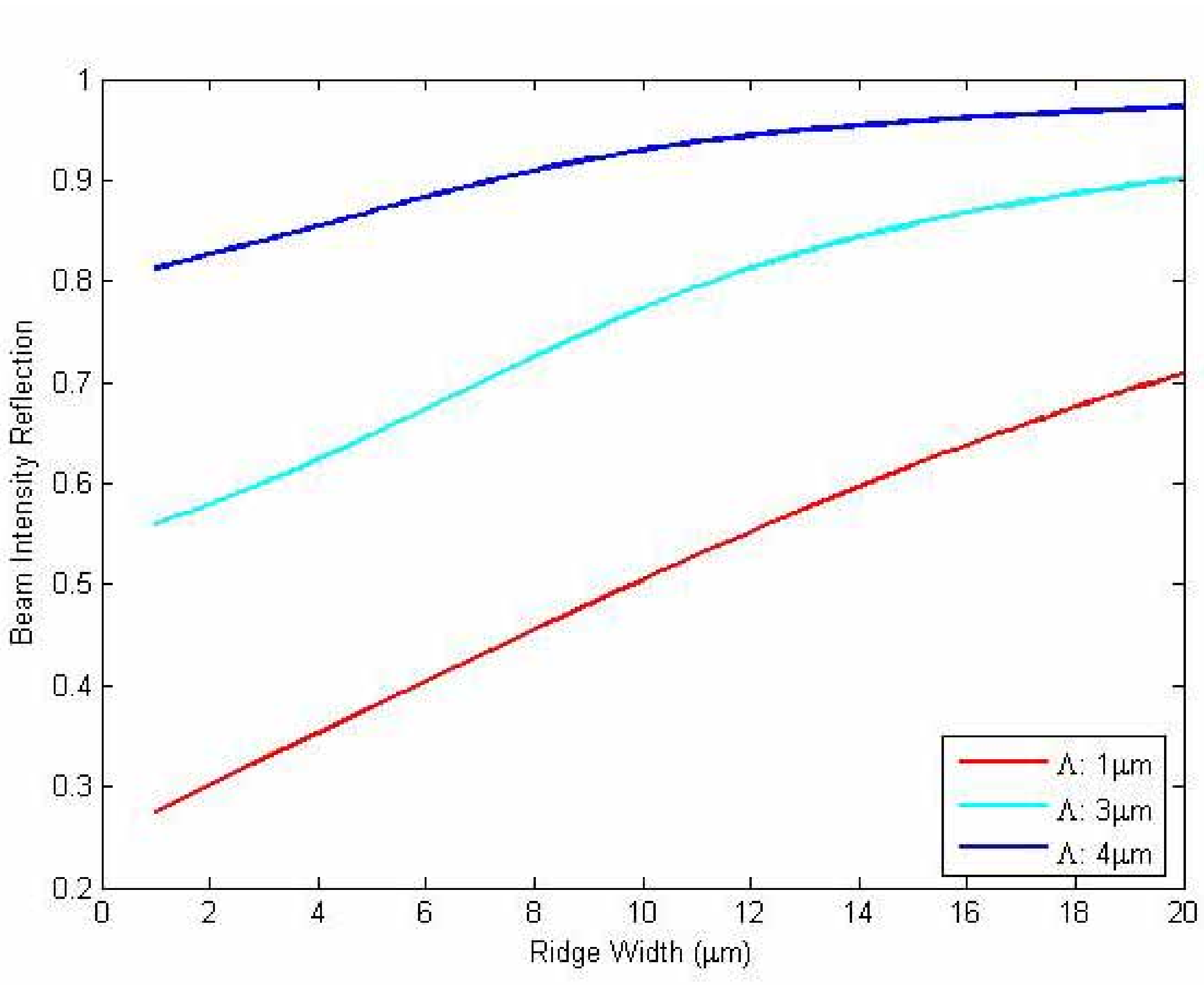


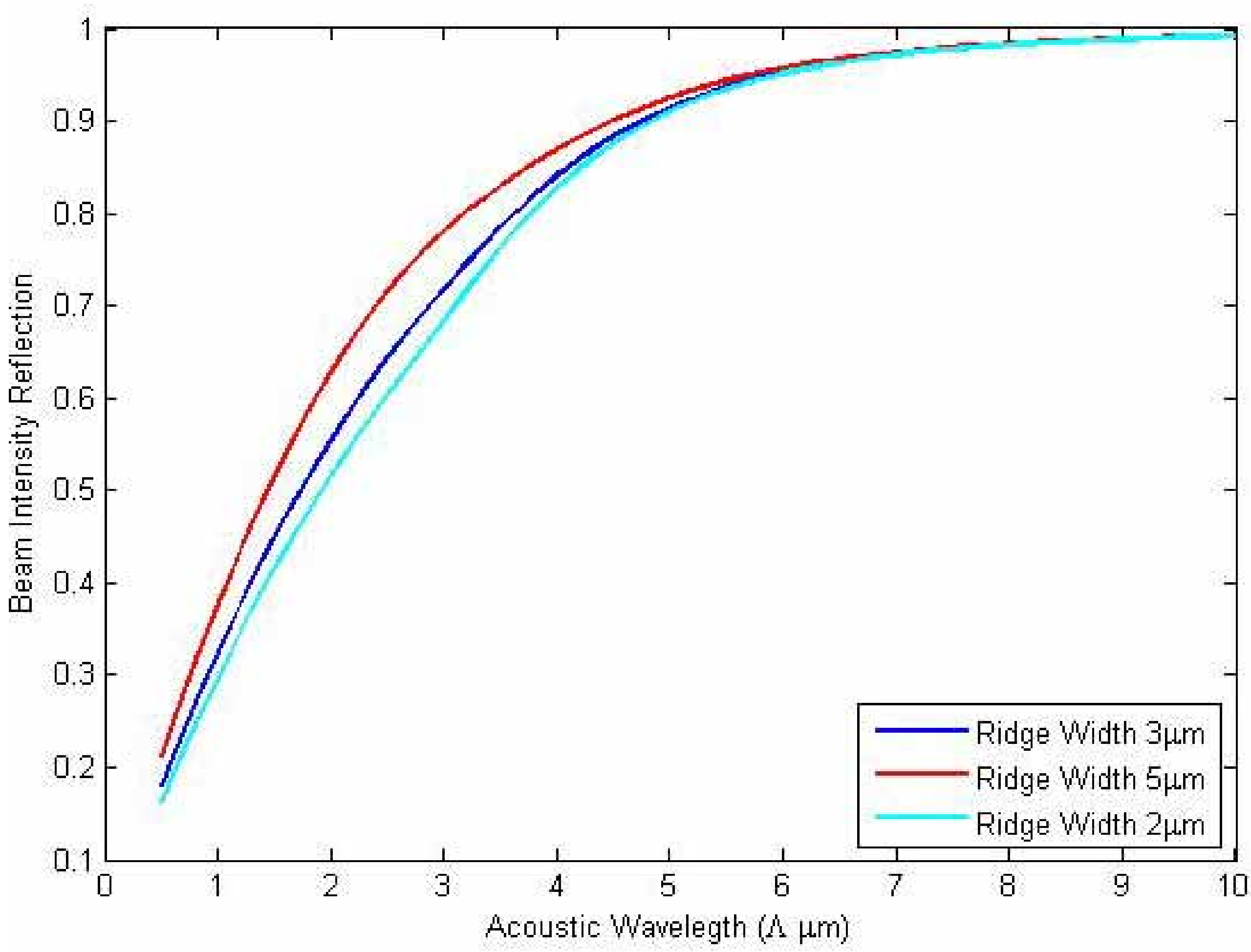
Ridge width: 5µm Λ: 4µm

Bragg angle

Summary

- Analysis of Integrated
  SAW and semiconductor optical source (GaN Laser/SLED)
- Multilayer SAW mode considered
- Lateral optical modes of Laser / SLED
- Included vertical optical modes in SAW region (EDC approximation)
- Approximated coupled wave diffraction analysis
- Results show acceptable SAW integrated functional device possible
- Need further refinements to the model


Beam Intensity Reflection
Ridge Width (µm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
2
4
6
8
10
12
14
16
18
20
Λ: 1µm
Λ: 3µm
Λ: 4µm


Beam Intensity Reflection
Acoustic Wavelegth (Λ μm)
Ridge Width 3μm
Ridge Width 5μm
Ridge Width 2μm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10