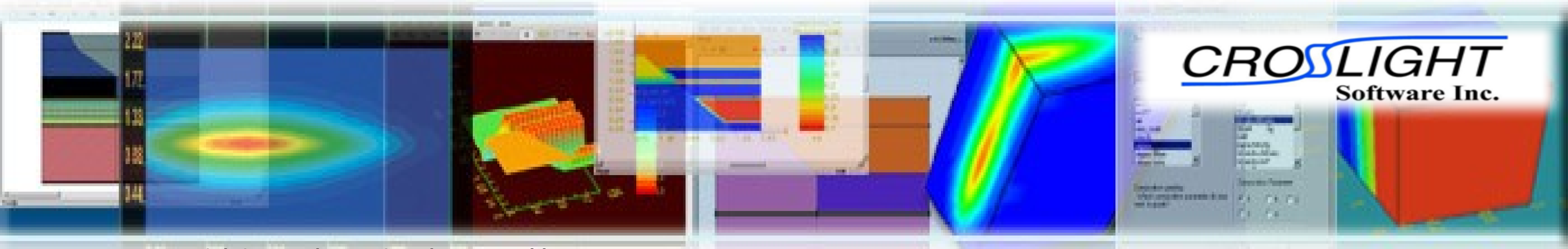


Lighting up the Semiconductor World…

Scalar and Vectorial Optical Mode solvers in VCSEL simulation

Optical Mode solver

- Optical mode solver
  - Used to calculate the possible optical modes that can resonate within the optical cavity.
    - For each mode, it is required to calculate electromagnetic field intensity and the resonance wavelength.
- Optical mode solver depends on:
  - Geometry of the structure
  - Material parameters of each layer of structure.
- Available solvers:
  - Scalar solvers
  - Vectorial solvers

The Scalar Solver

- Based on Hadley's Effective Index method
  - Use the scalar wave equation to solve for the resonance modes
    - Solve only for E-Fields.
  - Assume that VCSEL structure depends only on z within each number of concentric cylindrical region
    - Use the separation of variables to reduce the problem to a two 1D problem (solve for r-direction and z-direction separately)
      - Solve for longitudinal and transverse modes separately

Scalar wave Equation: Solve for E-Field

$$\nabla^2 E + k_0^2 \varepsilon E = 0$$

Separation of Variables : Mostly simply the problem to 1D

$$E(r,\phi,z) = \varphi(z).E(r,\phi)$$

G. Ronald Hadley, "Effective index model for vertical-cavity surface-emitting lasers," Opt. Lett. **20**, 1483-1485 (1995)

The Scalar Solver

- Based on the Hadley's Effective Index method
- Advantage of Scalar Solver
  - Reduce the computational resources
    - Memory and computational time.
- Limitations of Scalar Solver
  - Resonance calculations are accurate for the dominant mode only
    - Other parameters (threshold gain) are inaccurate (<10% difference compared to vectorial methods)
  - Scalar solvers are inaccurate in calculating:
    - Higher order modes
    - VCSEL with small dimensions

Scalar wave Equation: Solve for E-Field

$$\nabla^2 E + k_0^2 \varepsilon E = 0$$

Separation of Variables : Mostly simply the problem to 1D

$$E(r,\phi,z) = \varphi(z).E(r,\phi)$$

G. Ronald Hadley, "Effective index model for vertical-cavity surface-emitting lasers," Opt. Lett. **20**, 1483-1485 (1995)

The Full Vectorial Solver

Vectorial Solvers

- Based on Maxwell's equations
  - Solve for E-Fields and H-Fields
- Reduce the Cylindrical 3D VCSEL to a 2.5D problem
  - Using the symmetry of the VCSEL, the phi-variation can be expressed as exponential term
    - n_ϕ is the azimuthal mode number (integer)
      - For TE/TM modes
        - $n_\phi = 0$
      - For HE/EH modes
        - $n_\phi = 1,2,3,4,....$
  - Solve the full 2.5D problem
    - The fields are calculated in with respect to r-direction and z-direction **AT THE SAME TIME**

$$\nabla \times E = -j\omega\mu H$$

$$\nabla \times H = +j\omega\varepsilon E$$

$$\nabla \cdot D = 0$$

$$\nabla \cdot B = 0$$

Solve for both
E-field (E_r, E_z, E_φ)
H-field (H_r, H_z, H_φ)

Reduction from 3D → 2.5D

$$E(r,\phi,z) = E(r,z)e^{jn_\phi \phi}$$

$$H(r,\phi,z) = H(r,z)e^{jn_\phi \phi}$$

The Full Vectorial Solver

Vectorial Solvers

- Based on Maxwell's equations
- Reduce the Cylindrical 3D VCSEL to a 2.5D problem
- Advantages of full vectorial solver
  - Accurately calculates for:
    - All mode types (dominant mode as well as higher order modes).
    - Small structure dimensions (compared to resonance wavelength)
    - Other resonance mode parameters.
- Drawback of full vectorial solver
  - Since the full vectorial solver analyze the whole 2D structure:
    - It takes significantly more simulation time and memory.
    - The computational resources (Memory and simulation time) depend on the structure complexity

$$\nabla \times E = -j\omega\mu H$$

$$\nabla \times H = +j\omega\varepsilon E$$

$$\nabla \cdot D = 0$$

$$\nabla \cdot B = 0$$

Solve for both
E-field (E_r, E_z, E_φ)
H-field (H_r, H_z, H_φ)

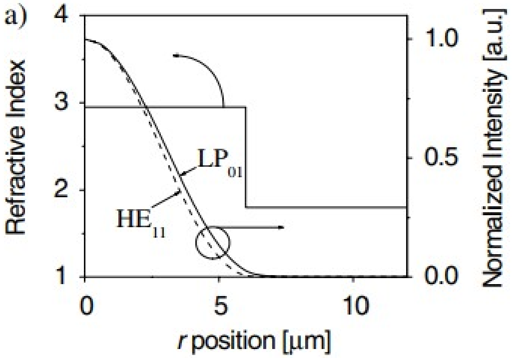
Reduction from 3D → 2.5D

$$E(r,\phi,z) = E(r,z)e^{jn_\phi \phi}$$

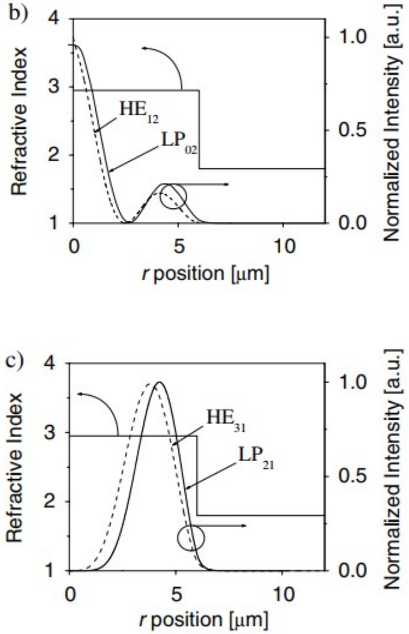
$$H(r,\phi,z) = H(r,z)e^{jn_\phi \phi}$$

Difference between Scalar and Full Vectorial modes

- Full vectorial modes have better confinement inside the active region compared to scalar ones.
  - For Large oxide-aperture
    - The difference is slight in the dominant mode
    - But for higher order modes, the difference becomes more obvious.



Dominant mode

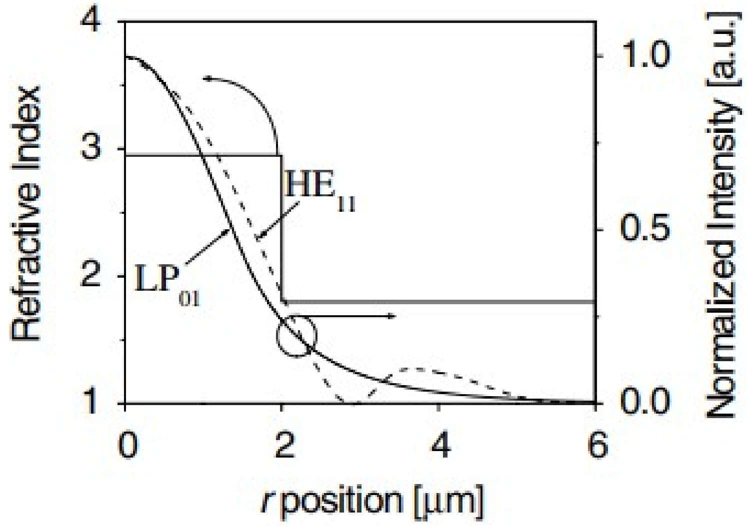


Higher order modes

Tomasz Czyszanowski and Włodzimierz Nakwaski 2006 *J. Phys. D: Appl. Phys.* **39** 30

Difference between Scalar and Vectorial Solver

- Full vectorial modes have better confinement inside the active region compared to scalar ones.
  - For Large oxide aperture
  - For smaller oxide aperture
    - Both scalar and full vectorial modes show a mode leakage into the passive region.
    - However, the oscillation behavior of the mode due to the diffraction is ONLY recognized by the full vectorial one.

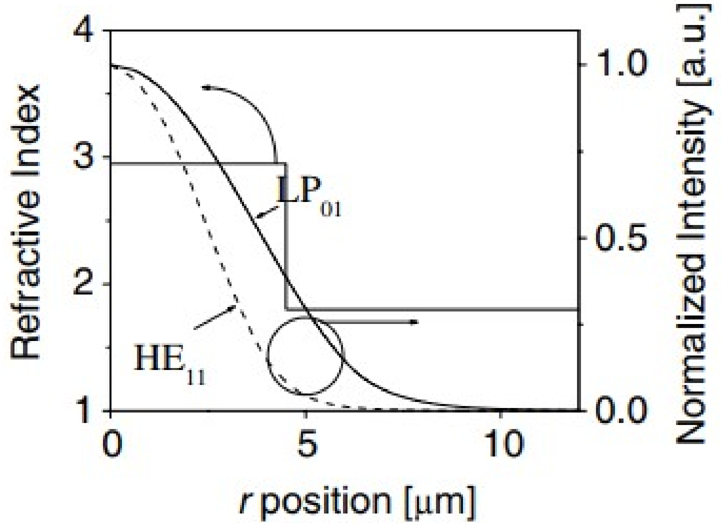


Dominant mode

Tomasz Czyszanowski and Włodzimierz Nakwaski 2006 *J. Phys. D: Appl. Phys.* **39** 30

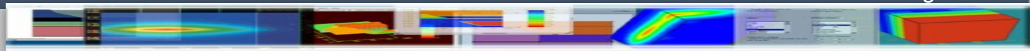
Difference between Scalar and Vectorial Solver

- Full vectorial modes have better confinement inside the active region compared to scalar ones.
  - For Large oxide aperture
  - For smaller oxide aperture
  - For narrow oxide layer
    - For narrow oxide layer, the mode suffers from diffraction losses
    - The diffraction loss effect is more sever in the case of the scalar mode.
    - This effect is more sever in higher order modes



Dominant mode

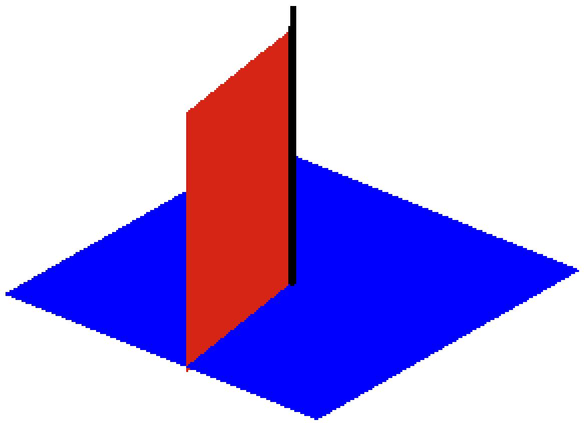
Tomasz Czyszanowski and Włodzimierz Nakwaski 2006 *J. Phys. D: Appl. Phys.* **39** 30



Crosslight VCSEL Model

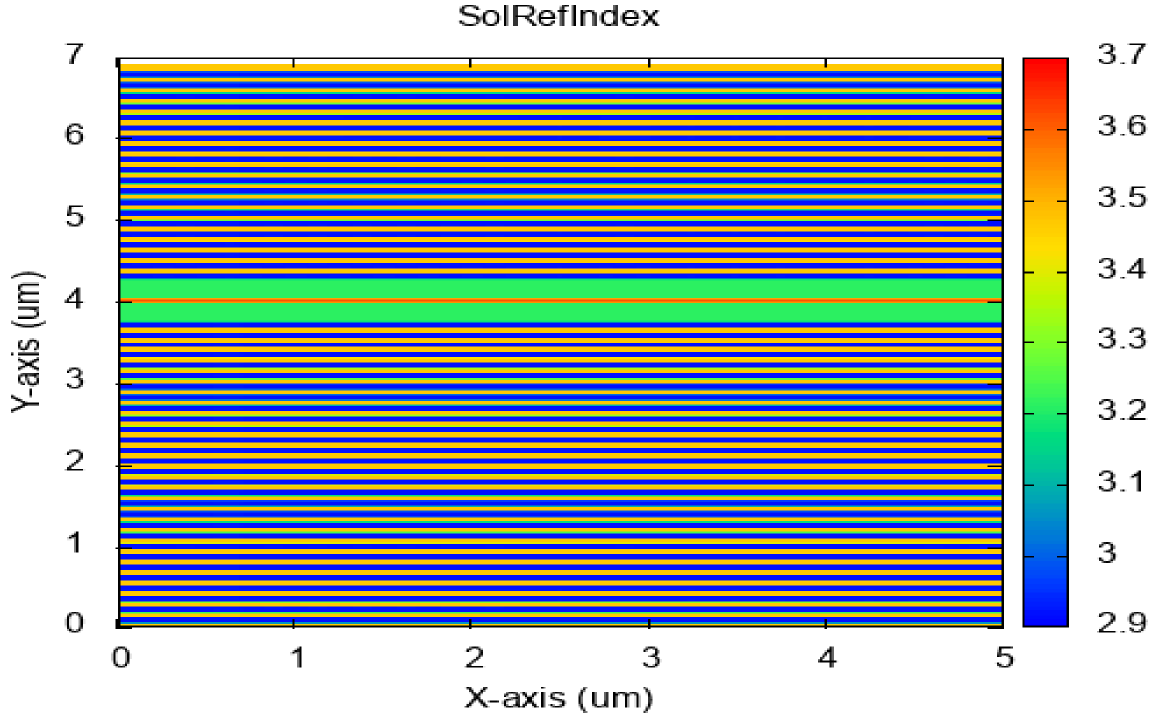
Cylindrical VCSEL

- VCSEL is a cylindrical structure (r,ϕ,z)
- Taking advantage of symmetry
  - Analytically include the φ-variation in the full vectorial model
  - Reduce the problem from 3D problem to 2.5D
    $E(r,\varphi,z) \rightarrow H(r, z).e^{+jn\varphi}$
    $H(r,\varphi,z) \rightarrow E(r, z).e^{+jn\varphi}$
    - By default the optical solver solves for
      - TE/TM modes
        - n = 0
      - HE/EH modes
        - n = 1,2,3,4,5



VCSEL structure

- Ref VCSEL
  - Bottom DBR
    - 29 layer ($Al_xGa_{1-x}As$)
      - X=0.25 / thick = 0.0595
      - X=1.00 / thick = 0.0706
  - Top DBR
    - 20 layer ($Al_xGa_{1-x}As$)
      - X=0.25 / thick = 0.0595
      - X=1.00 / thick = 0.0706
  - Cavity
    - Spacer
    - QW



VCSEL radius = 5μm

VCSEL Simulation Results

- Using Crosslight PICS3D, the following optical modes were calculated

```
 Found FDFD resonant modes at wavelength & imag_k(1/m):
    1  0.838642       101.198      HE-EH1
    2  0.838418       100.229      TE
    3  0.838398       101.253      HE-EH2
    4  0.838380       102.210      TM
    5  0.838091       100.232      HE-EH1
    6  0.838078       101.344      HE-EH3
    7  0.837959       102.309      HE-EH1
    8  0.837703       100.026      HE-EH2
    9  0.837686       101.487      HE-EH4
   10  0.837529       98.0510      TE
```

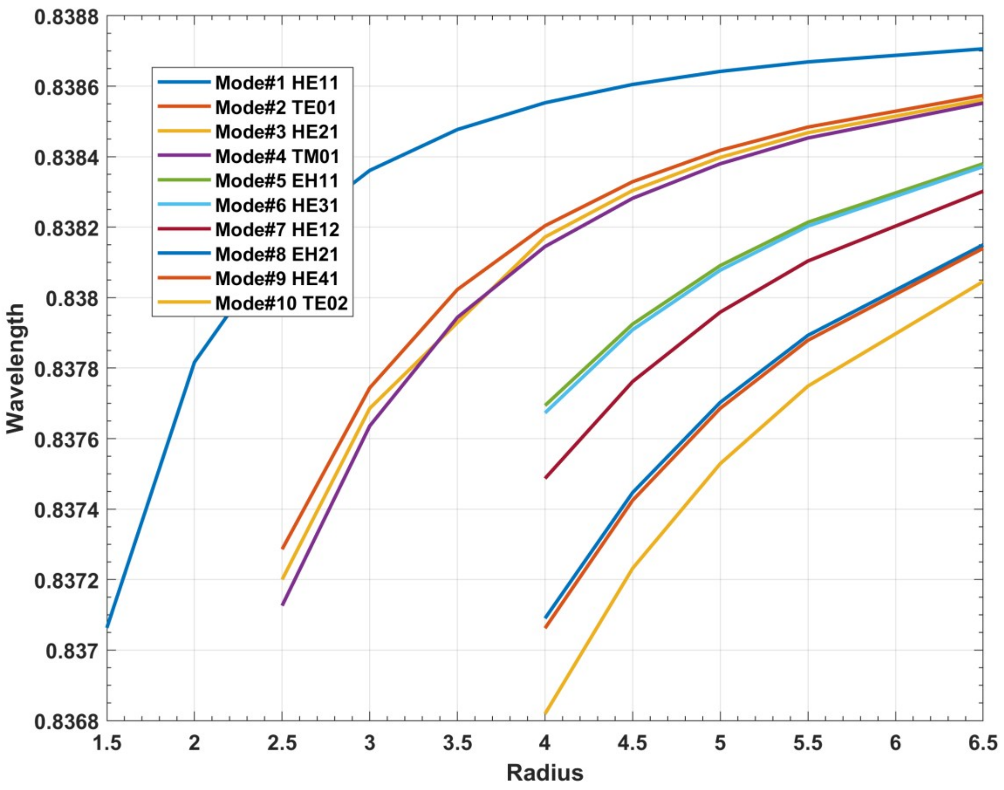
VCSEL Simulation Results

- Using Crosslight PICS3D, the following optical modes were calculated
- Calculated optical mode types

	Crosslight mode Name	Phi variation	# peaks	Equivalent mode Name
1	HE-EH1	1	1	HE11
2	TE	0	1	TE01
3	HE-EH2	2	1	HE21
4	TM	0	1	TM01
5	HE-EH1	1	1	EH11
6	HE-EH3	3	1	HE31
7	HE-EH1	1	2	HE12
8	HE-EH2	2	1	EH21
9	HE-EH4	4	1	HE41
10	TE	0	2	TE02

VCSEL Simulation Results

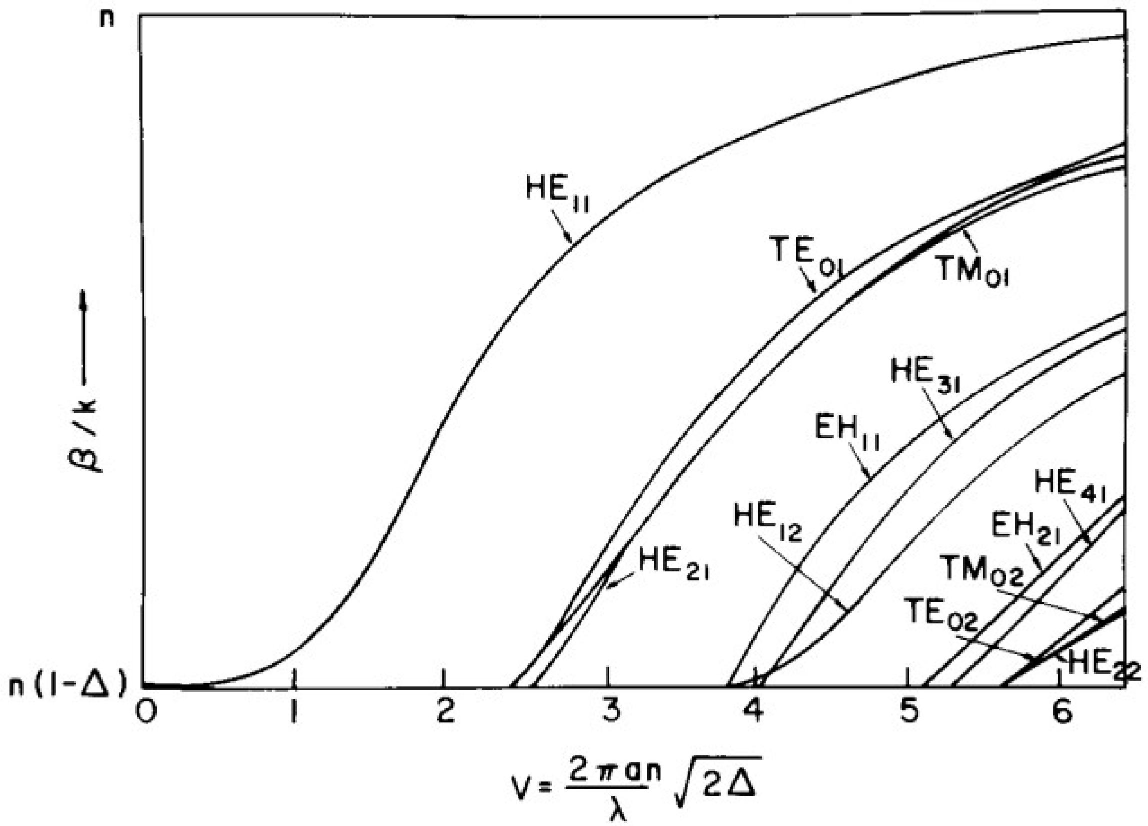
- Using Crosslight PICS3D, the following optical modes were calculated
- Calculated optical mode types
- Simulated optical modes at different VCSEL radii.



VCSEL Simulation Results

Optical Mode Comparison

- Analytical optical mode order
  - The analytical modes have a good agreement with the calculated ones using Crosslight full vectorial solver

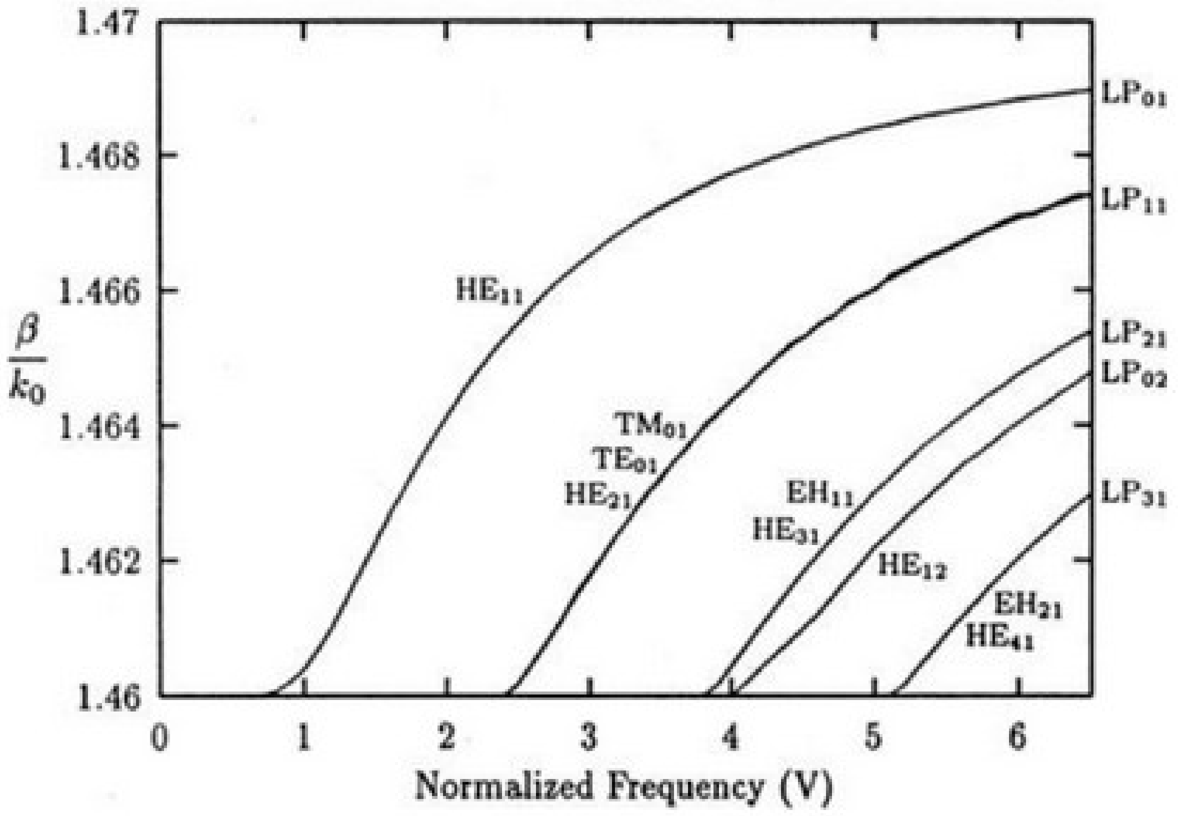


Barnoski, Michael K. 1981. *Fundamentals of optical fiber communications*. New York: Academic Press.

VCSEL Simulation Results

Optical Mode Comparison

- Analytical optical mode order
  - The analytical modes have a good agreement with the calculated ones using Crosslight full vectorial solver
  - These modes are similar to the LP modes

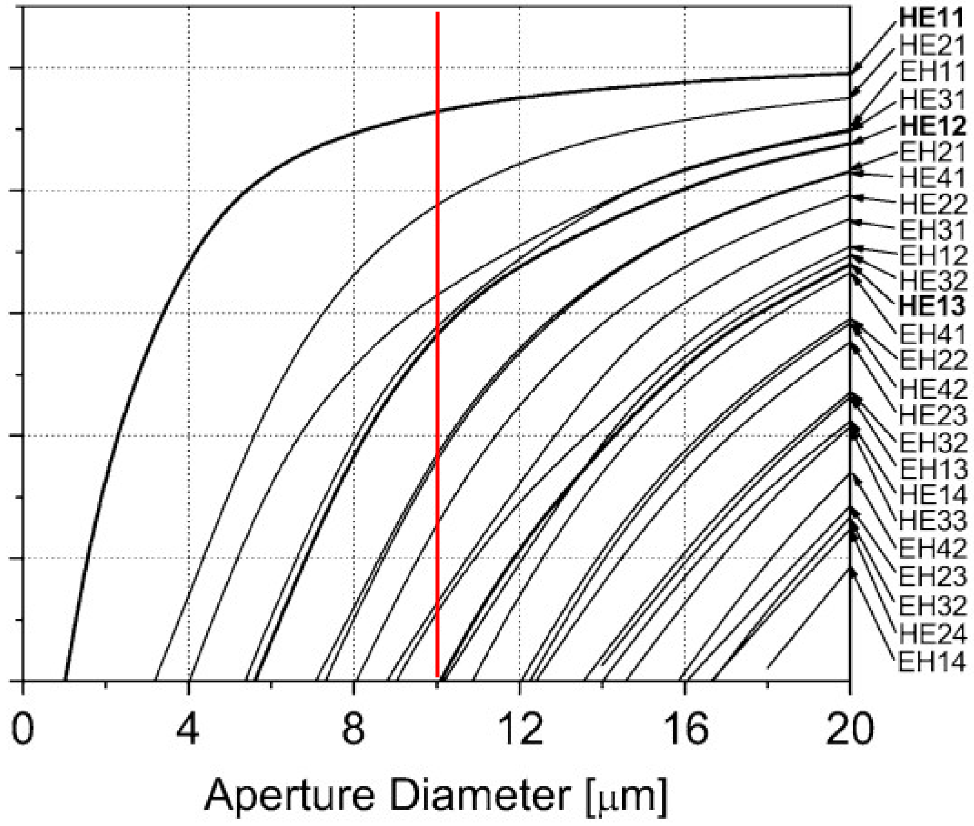


Barnoski, Michael K. 1981. *Fundamentals of optical fiber communications*. New York: Academic Press.

VCSEL Simulation Results

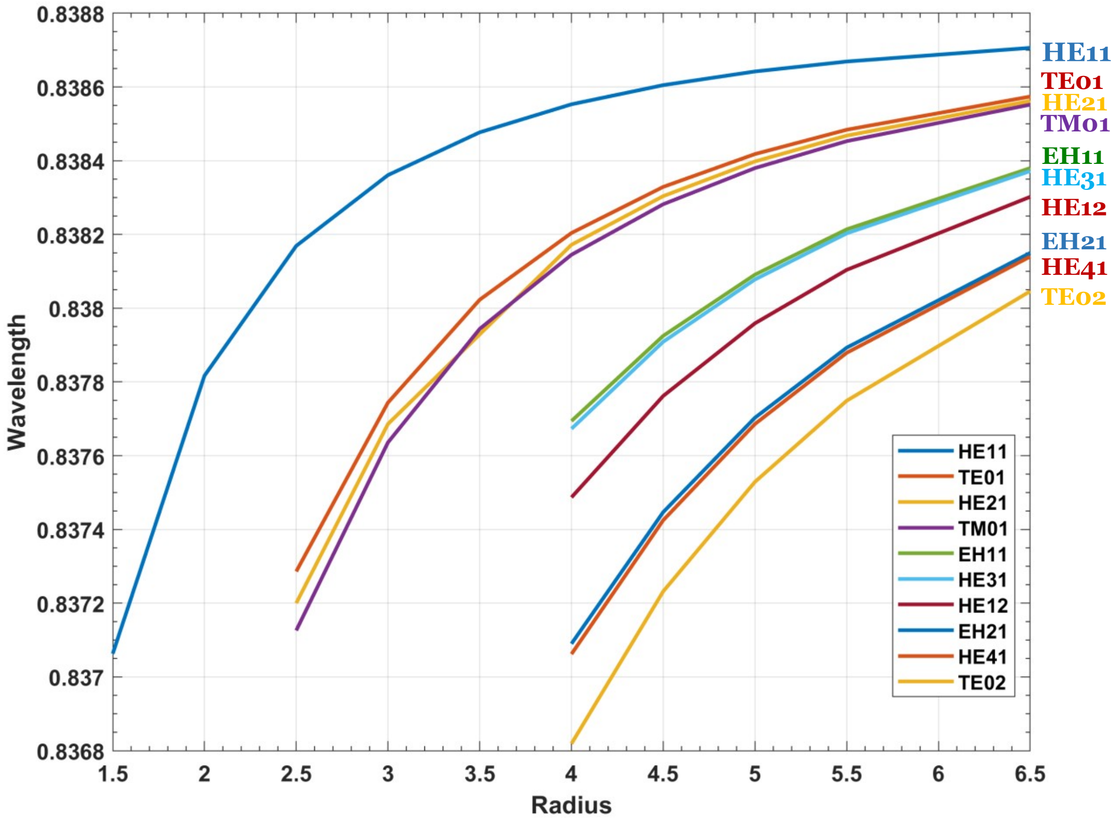
Optical Mode Comparison

- Analytical optical mode order
- Published results
  - Paper: “Comparison of Exactness of Scalar and Vectorial Optical Methods Used to Model a VCSEL Operation”.
  - Published Full vectorial solver
    - Method of Lines
    - Only solves for the HE/EH modes
  - The modes are in the same order as calculated using Crosslight full vectorial optical mode solver.

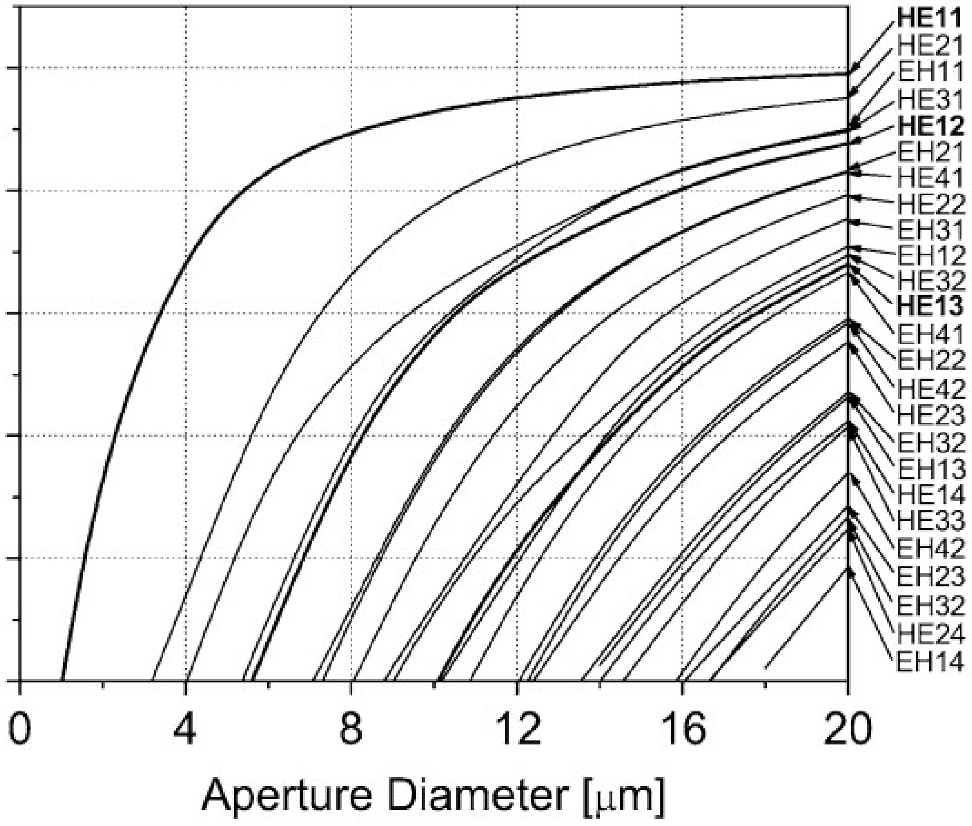


T. Czyszanowski and W. Nakwaski, "Comparison of Exactness of Scalar and Vectorial Optical Methods Used to Model a VCSEL Operation," in *IEEE Journal of Quantum Electronics*, vol. 43, no. 5, pp. 399-406, May 2007, doi: 10.1109/JQE.2006.894738.

VCSEL Simulation Results



Crosslight Full Vectorial Mode Solver



Published optical mode results

Conclusion

- The key differences between the scalar and full vectorial solvers are investigated.
- Crosslight VCSEL full vectorial optical mode solver calculates
  - TE/TM modes (n_ϕ=0)
  - HE and HE modes (n_ϕ=1,2,3,4,5)
- Simulation results of the Crosslight full vectorial VCSEL mode solver has a very good agreement with both the analytical results (for standard VCSEL) and published data.

Thank you