Direct Semiconductor Diode Laser Mode Engineering and Waveguide Design

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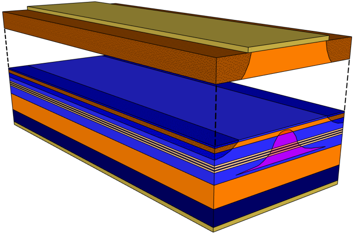
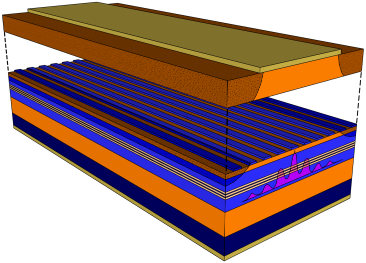
Mode Engineering: Motivation

Mode engineering is about controlling the lasing modes:

- Most applications want single lasing mode
- For many applications the fundamental Gaussian-like mode/beam is preferred
- Some applications want/need novel beam shapes and properties
  - Non-diffracting beams
  - Self-healing beams
  - Accelerating beams
  - Etc...





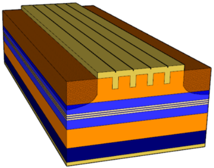
Three Forms of Mode Engineering

1. Modal Discrimination
   - Decrease the number of lasing modes
2. Modal Selection
   - Determine which cavity modes lase
3. **Direct Mode Engineering**
   - Engineer the lasing mode's field and properties

Direct Mode Engineering

In this talk:

- We consider the transverse modes and transverse index structure
- Solve the Helmholtz waveguide equation for the waveguide index structure
- Try to find practical approximations for the derived index structures
- Look at the Fourier optics far-field approximations for on-axis power
- Explore waveguide index structuring for engineering increased on-axis power for higher order modes



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Helmholtz Equation

$$\nabla^2 U(\vec{r}) + (n(\vec{r})^2 - \overline{n}^2) k_0^2 U(\vec{r}) = 0 \qquad (1)$$

- Transverse Modal Field $U(\vec{r})$
- Free-Space Wave-Vector k_0
- Waveguide Refractive Index Structure $n(\vec{r})$
- Modal Effective Refractive Index $\overline{n}$

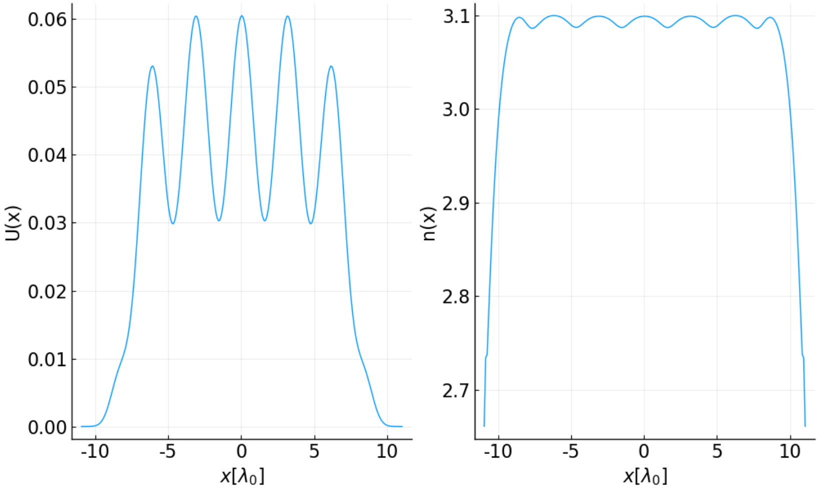
Helmholtz Equation Solution

Solve Helmholtz equation (1) for waveguide structure $n(\vec{r})$:

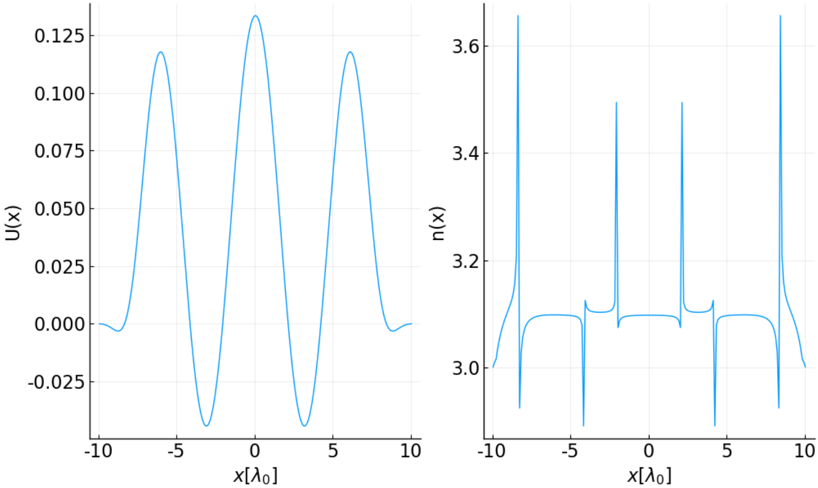
$$n(\vec{r}) = \sqrt{\overline{n}^2 - \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})}} \tag{2}$$

Let's try to find the supporting index structures for some fields.

Example


U(x)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
-10
-5
0
5
10
$x[\lambda_0]$
n(x)
3.1
3.0
2.9
2.8
2.7
-10
-5
0
5
10
$x[\lambda_0]$

Example



0.125
0.100
0.075
0.050
0.025
0.000
-0.025
U(x)
-10
-5
0
5
10
$x[\lambda_0]$
3.6
3.4
3.2
3.0
n(x)
-10
-5
0
5
10
$x[\lambda_0]$

Limitations on Modal Fields

Recall equation (2):

$$n(\vec{r}) = \sqrt{\overline{n}^2 - \boxed{\frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})}}}$$

$\frac{\nabla^2 U(\vec{r})}{U(\vec{r})}$ should be finite for modal field $U(\vec{r})$, otherwise $n(\vec{r})$ will have infinite values.

Provided $\frac{\nabla^2 U(\vec{r})}{U(\vec{r})}$ *is finite, can we obtain a reasonable index structure (one that is bounded to an implementable index value range)?*

Yes!

Normalizing Field for Refractive Index Range

We can transversely scale the field by a factor of α ($U_{\text{normalized}}(\vec{r}) = U(\alpha\vec{r})$) and choose $\overline{n}$ as to obtain a waveguide structure within a given index range $n_{\min} \leq n(\vec{r}) \leq n_{\max}$:

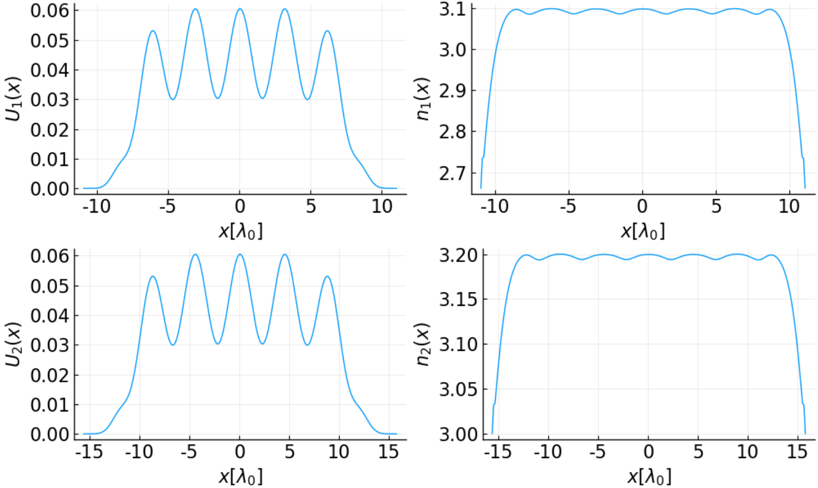
$$\overline{n} = \sqrt{\frac{n_{\max}^2 \chi_{\max} - n_{\min}^2 \chi_{\min}}{\chi_{\max} - \chi_{\min}}} \tag{3}$$

$$\alpha = \sqrt{\frac{n_{\max}^2 - n_{\min}^2}{\chi_{\max} - \chi_{\min}}} \tag{4}$$

$$\chi_{\min} = \min \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})} \tag{5}$$

$$\chi_{\max} = \max \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})} \tag{6}$$

Example: Normalize to $3.0 \leq n(r) \leq 3.2$

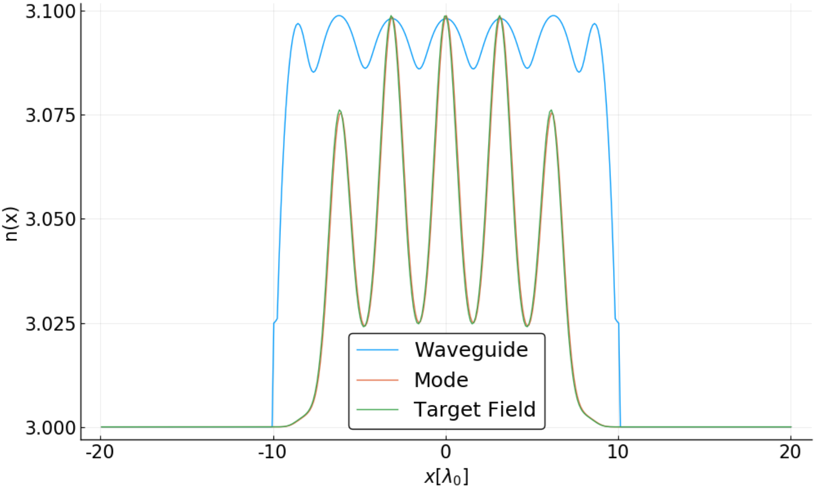


Approximating Waveguide Index Structure

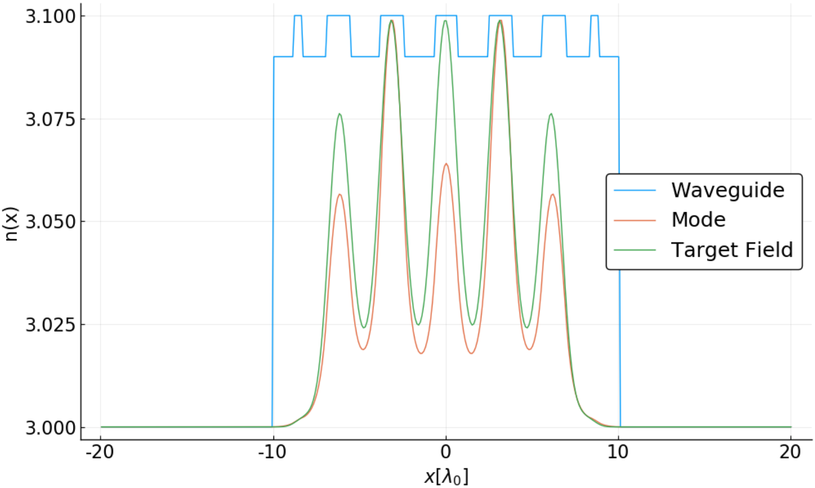
However, we need to approximate these index structures:

- For a given $U(r)$ equation (2) defines the index everywhere. Can we extract a finite width core region and add some cladding?
  - *Generally, Yes.*
- Continuously varied index not alway possible or practical. Can we approximate using discrete index values?
  - *Maybe. Simply clipping the index values may not yield optimal or sufficient approximation, but may be a good starting place for finding a better approximation.*

Approximating Waveguide Index Structure: Cladding



Approximating Waveguide Index Structure: Clip Index



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Fourier Optics Far-Field Approximations

Consider the Fraunhofer diffraction approximation:

$$U_2(x_2) \propto \int U_1(x_1) e^{-i\frac{kx_1x_2}{z}} dx_1$$

- Near-Field $U_1(x_1)$
- Far-Field $U_2(x_2)$
- Wave-Vector k
- Propagation distance z

The integral is a Fourier Transform from near-field to far-field

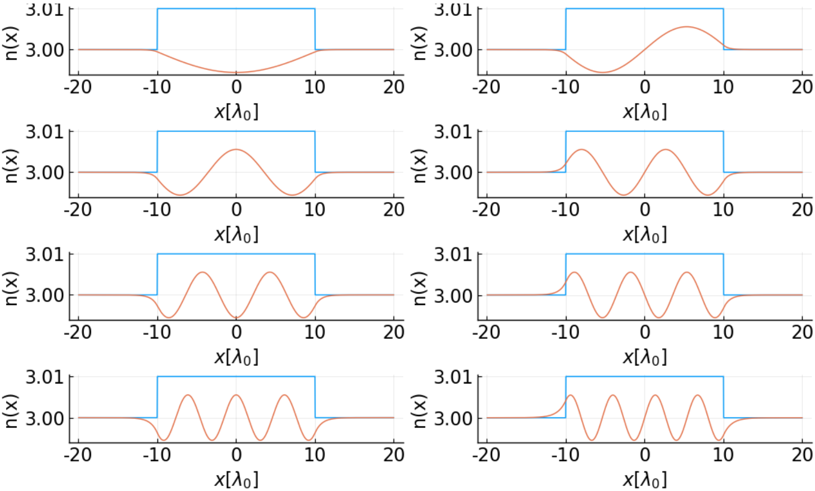
On-Axis Intensity

On-axis ($\theta = 0$) intensity:

$$|U_2(\theta = 0)|^2 \propto \left| \int U_1(x_1) dx_1 \right|^2$$

Consider the simple slab waveguide...

Simple Slab Waveguide Modes



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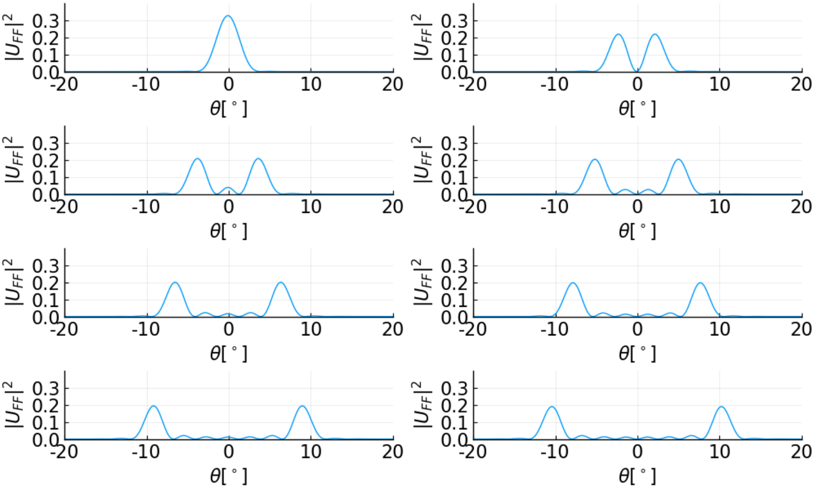
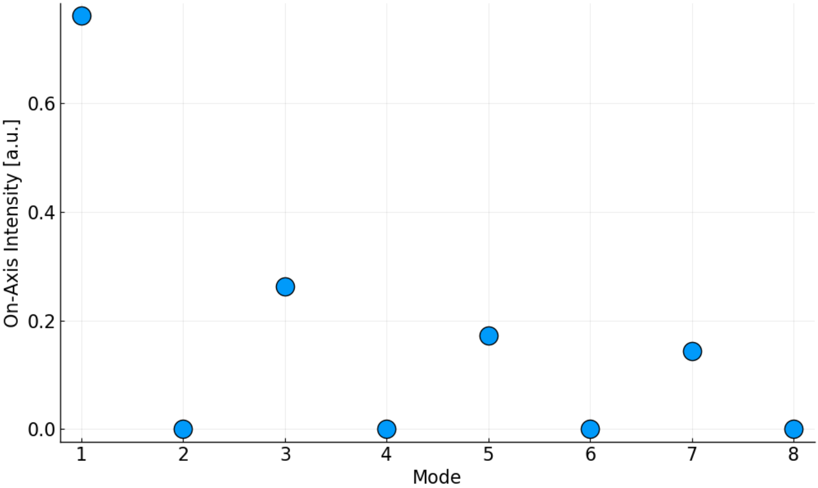
Simple Slab Waveguide Far-Fields



Simple Slab Waveguide On-Axis Intensity



Simple Slab Waveguide

Remarks:

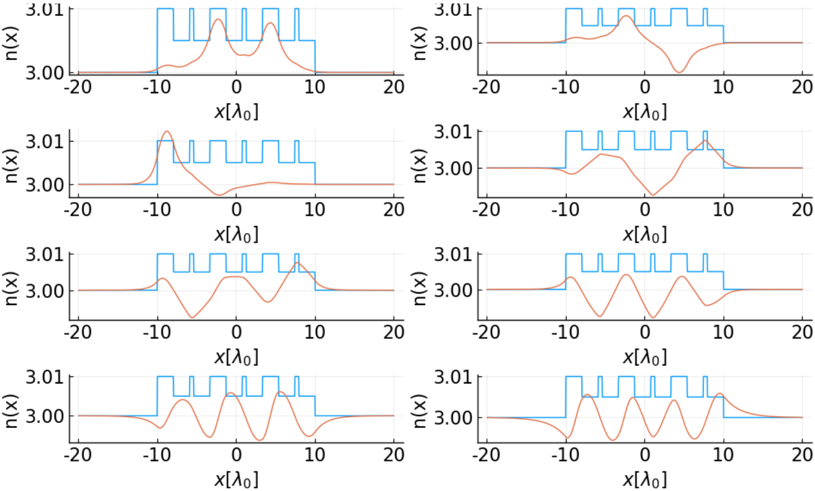
- Modes alternate between symmetric and anti-symmetric
- Symmetric modes have far-field on-axis lobe, anti-symmetric have on-axis null
- On-axis intensity decreases with increasing mode order

Engineered Waveguide

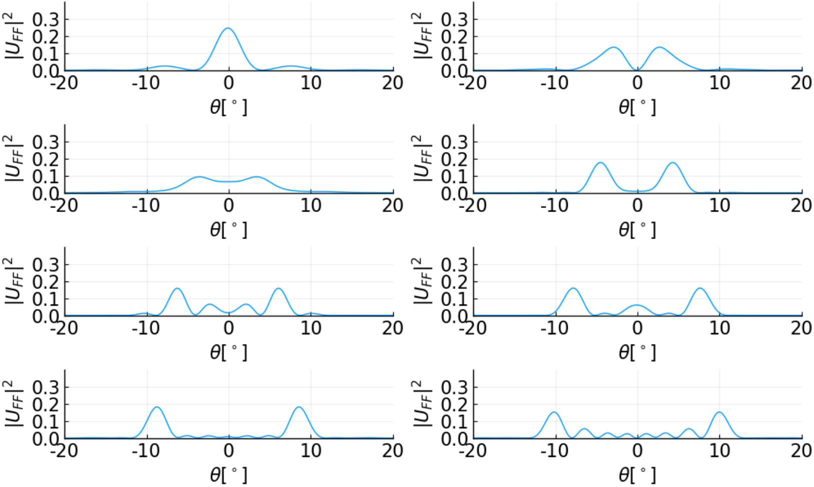
To try to change those trends:

- Break the waveguide structure mirror symmetry to avoid anti-symmetric modes
- Engineer mode with power concentrated within lobes of the same phase

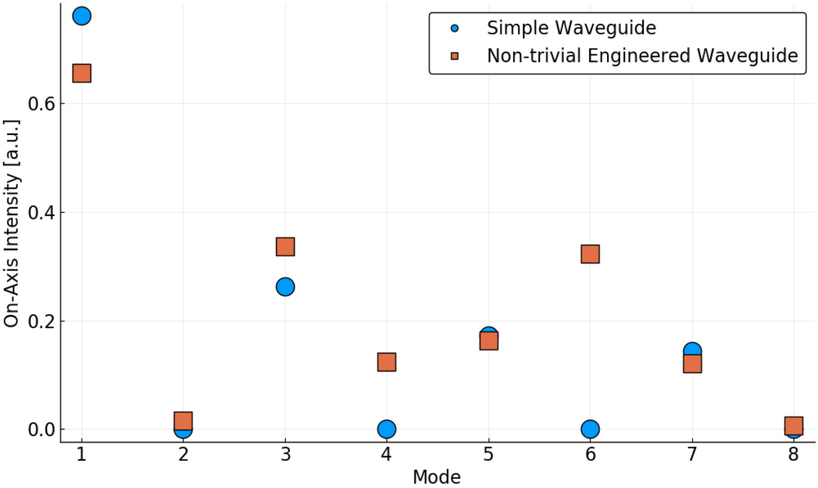
Example: Engineered Waveguide Modes



Example: Engineered Waveguide Far-Fields



Example: Engineered Waveguide On-Axis Intensity



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Conclusion

- Given a desired modal field, we can calculate a set of waveguide index structures that would support it
- If the solutions are not practical itself, we may be able to use it to get practical approximate structures
- Engineering the waveguide index structure can allow for improved on-axis intensity (even in higher-order modes that would have on-axis nulls in simple slab waveguides)

Thank you. Questions?