Objective
To design single-mode optical waveguides by simulation using MATLAB. Materials and dimensions are the design variables.

Simulation Environment/Materials
MATLAB application, computer

Hypothesis
The number of optical modes is expected to increase as $t_2$ increases because

In this experiment $t_2$ and “thickness of the middle layer” are used interchangeably.

Procedure
1. Download posted files into a folder (eg, C:\)
2. Launch MATLAB
3. Go to ‘Current Directory’ and select the folder where the files are downloaded
4. At the prompt, type Sample
5. For the first materials system,

SYS1
Top cladding: air ($n=1$);
Waveguide layer: silica ($n=1.45$);
Bottom cladding: air ($n=1$).

Enter the refractive index of the top layer, $n_1 = 1$
Enter the refractive index of the middle layer, \( n_2 = 1.45 \)
Enter the refractive index of the bottom layer, \( n_3 = 1 \)
Enter the thickness of the top layer, \( d_1 \) (um) = 5
Enter the thickness of the middle layer, \( d_2 \) (um) = 1
Enter the thickness of the bottom layer, \( d_3 \) (um) = 5
Enter the operating wavelength, \( \lambda \) (um) = 1.55
Enter the number of expected modes you want to see (or enter 0 to see ALL guided modes): 6

6. Increase \( t_2 \) until six optical mode graphs can be produced.

8. Now take the original parameters of SYS1 and set the number of expected modes you want to see equal to 0 (to show all optical modes) and vary \( t_2 \) with increments of 0.5 for 10 values. For ex. \( t_2 = 0.5, 1, 1.5, 2, 2.5 \ldots 5 \) . Note the effect on the number of optical modes and what value of \( t_2 \) yields a single-mode condition (where there is only one optical mode).

9. Repeat for three other systems

SYS2
Top cladding: \textbf{air (n=1)};
Waveguide layer: \textbf{silicon (n=3.48)};
Bottom cladding: \textbf{air (n=1)}.

SYS3 (optical fiber)
Top cladding: \textbf{silica (n=1.44)};
Waveguide layer: \textbf{doped silica (n=1.45)};
Bottom cladding: \textbf{silica (n=1.44)}.
[An example of a single-mode optical fiber has the following dimensions: \( t_1=5\)um, \( t_2=3\)um, \( t_3=5\)um]

SYS4 (a silicon-on-insulator SOI structure)
Top cladding: \textbf{silica (n=1.45)};
Waveguide layer: \textbf{silicon (n=3.48)};
Bottom cladding: \textbf{silica (n=1.45)}.

10. Note the two values of \( t_2 \) found from step 8 and 9, which show a change from a single optical mode to a second optical mode for each system. To three significant figures, find the critical thicknesses that yield this change.

11. Again take SYS1 with original parameters (step 5), set number of expected modes you want to see equal to 0, but now vary \( t_1 \) and \( t_3 \)-comment on the significance of these variables.
Data Collection

The following graphs display the first six optical modes; independent of dimensions.

First Optical Mode

Second Optical Mode

Third Optical Mode

Fourth Optical Mode

Fifth Optical Mode

Sixth Optical Mode
Given \( \lambda = 1.55 \, \mu m \) (IR wavelength) and \( \lambda = 0.650 \, \mu m \) (visible red light) and the other parameters as seen in Procedure, the following are plots of # of modes vs waveguide thickness \( t_2 \) for each of the 4 systems.

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>( t_2 )</th>
<th>NOM 1.55</th>
<th>NOM 0.650</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYS1</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>( t_2 )</th>
<th>NOM 1.55</th>
<th>NOM 0.650</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYS2</td>
<td>0.5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td></td>
<td>4.5</td>
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<tr>
<td></td>
<td>5</td>
<td>19</td>
<td>23</td>
</tr>
</tbody>
</table>

- **SYS1**
- **SYS2**
As can be seen by the graphs, as $t_2$ increases so does the number of optical modes. Number of modes also increases as the wavelength is decreased (from 1550 nm to 650 nm).

Furthermore, the $t_2$s that yields a single-condition mode for each of the four systems are the following:

- When changing $t_1$ and $t_3$, the number of optical modes did not change. Because the graphs of the optical modes are dimension independent, this means that $t_1$ and $t_3$ have no effect on the system.
To determine the behavior of the number of supported modes as a function of the thickness of the waveguide material, we have to first determine the relevant mathematical constraints and physical variables. There is the critical angle (denoted $\theta_c$) of the interface at the cladding and waveguide boundary, which in general should depend on the indices of refraction of the materials. The cladding index should of course be less than the waveguide index, but for our analysis to truly be relevant the cladding index should be close to that of vacuum to allow for a reasonable critical angle. Next, we have to determine what constraints there are on the maximum length $L$ of the standing wave, which will determine the number of supported modes $n$:

- $\cos \theta_c = \frac{t}{L}$, where $t$ is the thickness of the waveguide material.
- $L = \frac{t}{\cos \theta_c}$
- So now, how does $n$ change with $L$? $n$ varies as $L$ as a step function, linearly, with a constant of proportionality $C$ (determined experimentally) depending inversely on the wavelength $\lambda$. This is because we need integral multiples of the wavelength for each mode.
- $n = \lfloor \frac{L \times C}{\lambda} \rfloor$, where $\lfloor x \rfloor$ denotes greatest integer function of $x$.
- So, $n = \lfloor \frac{tC}{\lambda \cos \theta_c} \rfloor$

The first six modes are consistent for all systems since it is dimension independent. The graphs show the number of oscillations able to occur as the wave passes through. The higher the optical mode number, the greater number of “peaks” or crests occur—thus more oscillation.

As for the thickness of the cladding layer, it should be above a minimum thickness to effectively eliminate frustrated emission of light; otherwise, the thickness of the cladding layer has no effect on the results of the number of optical modes.

Since the optical mode of a beam is the intensity pattern of radiation measured perpendicular to the direction of propagation by the beam, and because these optical modes exist solely due to the boundary conditions impressed on the wave by our waveguide, the modes given in our experiment are quantized and are unaffected by surrounding insulating materials. Although theoretically, with a large enough distance or time interval for a given beam, one could observe a gradual decrease in the amplitudes of the waves as they propagate through the waveguide, and a considerable drop in energy due to dissipated energy from the absence of sufficient insulators $t_1$ and $t_3$ surrounding the waveguide layer $t_2$. This experiment, however, did not provide such an example.
The number of modes, $n$, depended linearly on our waveguide thickness $t_2$, as expected. As for varying the wavelength, the length of steps depends linearly on it, as expected, and the higher wavelength decreases the number of modes for a given setup, because it decreases the number of wavelengths that can be fit in the maximum ray length. Furthermore, as indicated by the graphs, a decrease in wavelength (from 1550 nm to 650nm) increased the mode, which represents the number of oscillations of the wave and consequently the associated energy.

Theoretically, given a large enough interval of distance or time, energy dissipation through the cladding layers will become evident. The rate of change of $n$ with respect to $t_2$ would depend inversely on the cosine of the critical angle, and this could be verified experimentally by observing that as the index of refraction of the cladding layer increases, the critical angle increases (or its cosine decreased), and the number of modes increases at a higher rate (with respect to $t_2$).

Regarding the cladding layers, experimentally $t_1$ and $t_3$ are irrelevant to the number of modes but are relevant to the existence of any modes in general, since theoretically we can assume that there is a threshold for a minimum thickness required to effectively reflect a beam. In other words, these thicknesses $t_1$ and $t_3$ determine whether the signal will be “leaked” due to frustration of the light, and must be above a certain minimum thickness (depending on the materials and the operating wavelength), however does otherwise not change the output of the system.