Model created in COMSOL Multiphysics 6.4

Step-Index Fiber

Introduction

The data transmission speed of optical waveguides is superior to microwave waveguides because optical devices have a much higher operating frequency than microwaves, enabling a far higher bandwidth.

Today the silica glass (SiO_2) fiber is forming the backbone of modern communication systems. Before 1970, optical fibers suffered from large transmission losses, making optical communication technology merely an academic issue. In 1970, researchers showed, for the first time, that low-loss optical fibers really could be manufactured. Earlier losses of 2000 dB/km now went down to 20 dB/km. Today's fibers have losses near the theoretical limit of 0.16 dB/km at 1.55 µm (infrared light).

One of the winning devices has been the single-mode fiber, having a step-index profile with a higher refractive index in the center core and a lower index in the outer cladding. Numerical software plays an important role in the design of single-mode waveguides and fibers. For a fiber cross section, even the simplest shape is difficult and cumbersome to deal with analytically. A circular step-index waveguide is a basic shape where benchmark results are available (see Ref. 1).

This example is a model of a single step-index waveguide made of silica glass. The inner core is made of pure silica glass with refractive index n_1 = 1.4457 and the cladding is doped with a refractive index of n_2 = 1.4378. These values are valid for free-space wavelengths of 1.55 µm. The radius of the cladding is chosen to be large enough so that the field of confined modes is zero at the exterior boundaries.

For a confined mode there is no energy flow in the radial direction, so the wave must be evanescent in the radial direction in the cladding. This is true only if

$$n_{\mathrm{eff}} > n_2$$

On the other hand, the wave cannot be radially evanescent in the core region. Thus

$$n_2 < n_{\mathrm{eff}} < n_1$$

The waves are more confined when n_{eff} is close to the upper limit in this interval.

Model Definition

The mode analysis is made on a cross section in the *xy*-plane of the fiber. The wave propagates in the *z* direction and has the form

$$\mathbf{E}(x, y, z, t) = \mathbf{E}(x, y)e^{j(\omega t - \beta z)}$$

where ω is the angular frequency and β the propagation constant. An eigenvalue equation for the electric field $\mathbf{E}$ is derived from Helmholtz equation

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 n^2 \mathbf{E} = \mathbf{0}$$

which is solved for the eigenvalue $\lambda = -j\beta$.

As boundary condition along the outside of the cladding, the electric field is set to zero. Because the amplitude of the field decays rapidly as a function of the radius of the cladding this is a valid boundary condition.

Results and Discussion

When studying the characteristics of optical waveguides, the effective mode index of a confined mode,

$$n_{\mathrm{eff}} = \frac{\beta}{k_0}$$

as a function of the frequency is an important characteristic. A common notion is the normalized frequency for a fiber. This is defined as

$$V = \frac{2\pi a}{\lambda_0}\sqrt{n_1^2 - n_2^2} = k_0 a \sqrt{n_1^2 - n_2^2}$$

where a is the radius of the core of the fiber. For this simulation, the effective mode index for the fundamental mode, 1.4444 corresponds to a normalized frequency of 4.895. The longitudinal components of the electric and magnetic fields for this mode is shown in Figure 1 below.

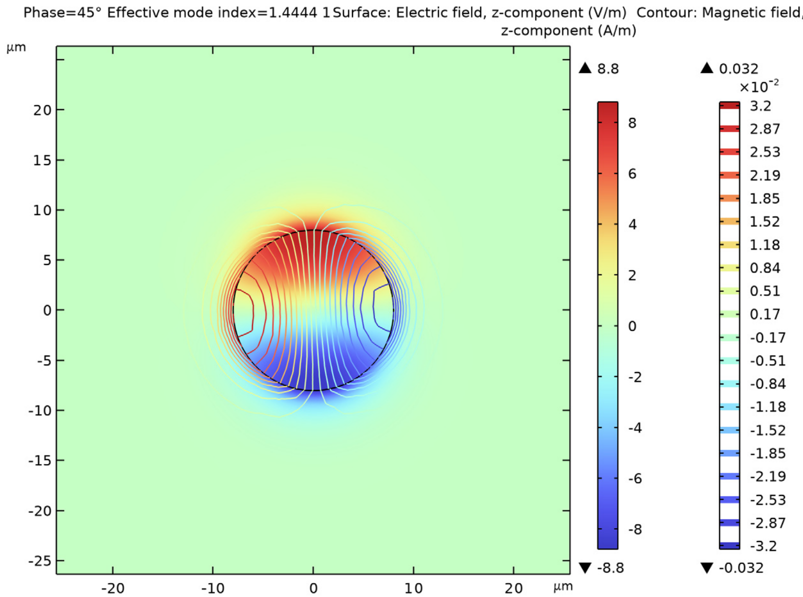


Figure 1: The surface plot visualizes the z component of the electric field. This plot is for the effective mode index 1.4444.

Reference

1. A. Yariv, *Optical Electronics in Modern Communications*, 5th ed., Oxford University Press, 1997.

Application Library path: `RF_Module/Tutorials/step_index_fiber`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.
2 In the **Select Physics** tree, select **Radio Frequency** > **Electromagnetic Waves, Frequency Domain (emw)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Mode Analysis**.
6 Click **Done**.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2 In the **Settings** window for **Geometry**, locate the **Units** section.
3 From the **Length unit** list, choose **µm**.

Circle 1 (c1)

1 In the **Geometry** toolbar, click **Circle**.
2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.
3 In the **Radius** text field, type `40`.
4 Click **Build Selected**.

Circle 2 (c2)

1 In the **Geometry** toolbar, click **Circle**.
2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.
3 In the **Radius** text field, type `8`.
4 Click **Build Selected**.

MATERIALS

Doped Silica Glass

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
2 In the **Settings** window for **Material**, type `Doped Silica Glass` in the **Label** text field.
3 Select Domain 2 only.
4 Click to expand the **Material Properties** section. In the **Material properties** tree, select **Electromagnetic Models** > **Refractive Index** > **Refractive index, real part (n)**.

5 Click **Add to Material**.

6 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	1.4457	1	Refractive index

Silica Glass

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Silica Glass` in the **Label** text field.

3 Select Domain 1 only.

4 Click to expand the **Material Properties** section. In the **Material properties** tree, select **Electromagnetic Models** > **Refractive Index** > **Refractive index, real part (n)**.

5 Click **Add to Material**.

6 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	1.4378	1	Refractive index

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

Keep the default physics settings, which include perfect electric conductor conditions for the outer boundaries.

Wave Equation, Electric 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain (emw)** click **Wave Equation, Electric 1**.

2 In the **Settings** window for **Wave Equation, Electric**, locate the **Electric Displacement Field** section.

3 From the **Electric displacement field model** list, choose **Refractive index**.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 In the table, clear the **Use** checkbox for **Electromagnetic Waves, Frequency Domain (emw)**.

4 From the **Element size** list, choose **Finer**.

5 Click **Build All**.

STUDY 1

Step 1: Mode Analysis

1 In the **Model Builder** window, under **Study 1** click **Step 1: Mode Analysis**.

2 In the **Settings** window for **Mode Analysis**, locate the **Study Settings** section.

3 Select the **Search for modes around shift** checkbox. In the associated text field, type `1.446`.

The modes of interest have an effective mode index somewhere between the refractive indices of the two materials. The fundamental mode has the highest index. Therefore, setting the mode index to search around to something just above the core index guarantees that the solver will find the fundamental mode.

4 In the **Mode analysis frequency** text field, type `c_const/1.55[um]`. This frequency corresponds to a free space wavelength of 1.55 µm.

5 In the **Study** toolbar, click **Compute**.

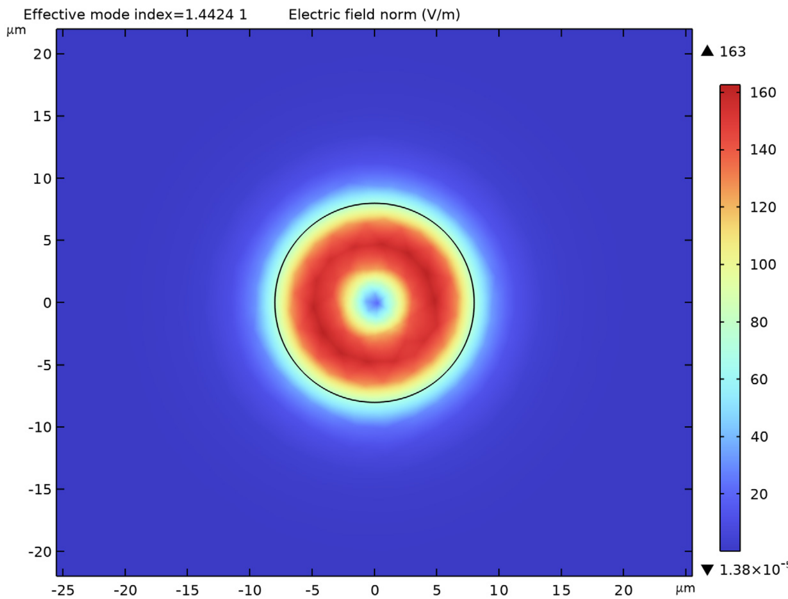
RESULTS

Electric Field (emw)

1 Click the **Zoom Extents** button in the **Graphics** toolbar.

2 Click the **Zoom In** button in the **Graphics** toolbar.

The default plot shows the distribution of the norm of the electric field for the highest of the 6 computed modes (the one with the lowest effective mode index).



To study the fundamental mode, choose the highest mode index. Because the magnetic field is exactly 90 degrees out of phase with the electric field you can see both the magnetic and the electric field distributions by plotting the solution at a phase angle of 45 degrees.

Study 1/Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Results** > **Datasets** node, then click **Study 1/ Solution 1 (sol1)**.

2 In the **Settings** window for **Solution**, locate the **Solution** section.

3 In the **Solution at angle (phase)** text field, type 45.

Electric Field (emw)

1 In the **Model Builder** window, under **Results** click **Electric Field (emw)**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Effective mode index (1)** list, choose **1.4444**.

Surface 1

1. In the **Model Builder** window, expand the **Electric Field (emw)** node, then click **Surface 1**.
2. In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Electric** > **Electric field - V/m** > **emw.Ez - Electric field, z-component**.
3. In the **Electric Field (emw)** toolbar, click **Plot**.

   Add a contour plot of the H-field.

Contour 1

1. In the **Model Builder** window, right-click **Electric Field (emw)** and choose **Contour**.
2. In the **Settings** window for **Contour**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Magnetic** > **Magnetic field - A/m** > **emw.Hz - Magnetic field, z-component**.
3. In the **Electric Field (emw)** toolbar, click **Plot**.

   The distribution of the transversal E and H field components confirms that this is the HE11 mode. Compare the resulting plot with that in Figure 1.