Step-Index Fiber

Introduction

The 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 centre 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 most simple 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, thus the wave must be evanescent in the radial direction in the cladding. This is true only if

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

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

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

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

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

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

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

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

As boundary condition along the outside of the cladding the magnetic 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

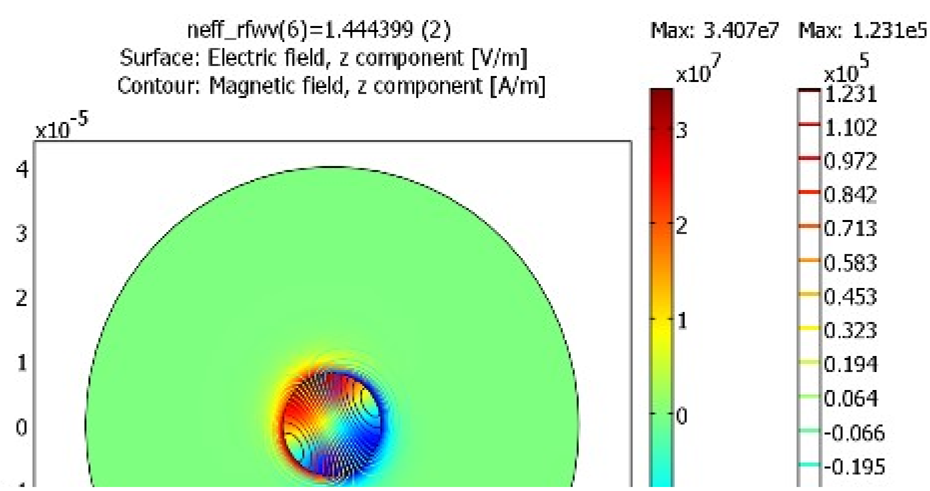
When studying the characteristics of optical waveguides, the effective mode index of a confined mode,

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

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 electric and magnetic fields for this mode is shown in Figure 4-10 below.



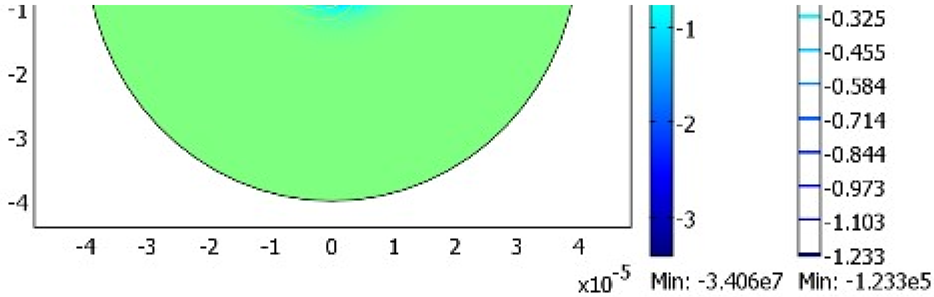


Figure 4-10: The surface plot visualizes the z component of the electric field, and the contour lines show the z component of the magnetic field. This plot is for the effective mode index 1.4444.

Reference

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

Model Library path: `RF_Module/Optics_and_Photonics/step_index_fiber`

Modeling Using the Graphical User Interface

MODEL NAVIGATOR

1 In the **Model Navigator**, select **2D** in the **Space dimension** list.

2 Select the **RF Module>Perpendicular Waves>Hybrid-Mode Waves>Mode analysis** application mode.

3 Click **OK**.

APPLICATION MODE PROPERTIES

1 Select **Properties** in the **Physics** menu to open the **Application Mode Properties** dialog box.

2 For convenience set the property **Specify wave using** to **Free space wavelength**. This makes the wavelength available in the **Application Scalar Variables** dialog box instead of the frequency.

OPTIONS AND SETTINGS

1 In the **Constants** dialog box, enter the following names and expressions for the refractive indices.

NAME	EXPRESSION
nSilicaGlass	1.4457
nSilicaGlassDoped	1.4378

GEOMETRY MODELING

1 Draw a circle C1 centered at (0,0) with radius 8e-6.

2 Draw a second circle C2 centered at (0,0). This time with the radius 40e-6.

3 Click the **Zoom Extents** button for a full visualization of the two circles.

PHYSICS SETTINGS

Scalar Variables

In the **Application Scalar Variables** dialog box, set the free space wavelength `lambda0_rfwv` to `1.55e-6`.

Boundary Conditions

Use the default boundary conditions on all exterior boundaries.

Subdomain Settings

In the **Subdomain Settings** dialog box enter the refractive index in the two domains according to the following table:

SETTING	SUBDOMAIN 1	SUBDOMAIN 2
n	`nSilicaGlassDoped`	`nSilicaGlass`

MESH GENERATION

1 Initialize the mesh.

2 Refine the mesh once.

COMPUTING THE SOLUTION

The modes of interest have an effective mode index somewhere between the refractive indices of the two materials, that is,

$$1.4378 < n_{\text{eff}} < 1.4457$$

1 In the **Solver Parameters** dialog box set the parameter **Search for effective mode indices around** to `1.446`. This guarantees that the solver will find the fundamental mode, which has the largest effective mode index.

2 Solve the problem.

POSTPROCESSING AND VISUALIZATION

The default plot shows the power flow in the z direction for the fundamental mode. This is the HE_{11} mode, which is verified by visualizing the transversal components of both the magnetic and the electric field.

1 In the **Plot Parameters** dialog box, select surface and contour plots.

2 Set **Solution at angle (phase)** to `45`.

3 On the **Surface** page, set the **Surface data** to **Electric field, z component**.

4 On the **Contour** page, give **Magnetic field, z component** as **Contour data**.