Integrated Square-Shaped Spiral Inductor

Introduction

This example presents a model of a micro-scale square inductor, used for LC bandpass filters in microelectromechanical systems (MEMS).

The purpose of the model is to calculate the self-inductance of the microinductor. Given the magnetic field, you can compute the self-inductance, L, from the relation

$$L = \frac{2W_m}{I^2}$$

where W_m is the magnetic energy and I is the current. The model uses the Terminal boundary condition, which sets the current to 1 A and automatically computes the self-inductance. The self-inductance L becomes available as the L_{11} component of the inductance matrix.

Model Definition

The model geometry consists of the spiral-shaped inductor and the air surrounding it. Figure 1 below shows the inductor and air domains used in the model. The outer dimensions of the model geometry are around 0.3 mm.

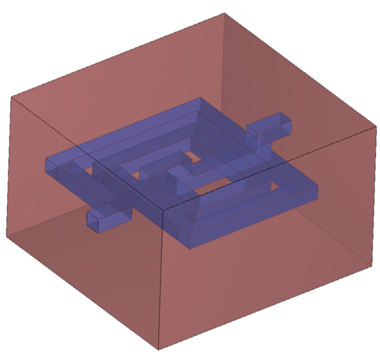

Figure 1: Inductor geometry and the surrounding air.

The model equations are the following:

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}^{e}) = 0$$
$$\nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times \mathbf{A}) + \sigma \nabla V = \mathbf{J}^{e}$$

In the equations above, σ denotes the electrical conductivity, $\mathbf{A}$ the magnetic vector potential, V the electric scalar potential, $\mathbf{J}^e$ the externally generated current density vector, μ_0 the permittivity in vacuum, and μ_r the relative permeability.

The electrical conductivity in the coil is set to 10^6 S/m and 1 S/m in air. The conductivity of air is arbitrarily set to a small value in order to avoid singularities in the model, but the error becomes small as long as the value of the conductivity is small.

The constitutive relation is specified with the expression

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$

where $\mathbf{H}$ denotes the magnetic field.

The boundary conditions are of three different types corresponding to the three different boundary groups; see Figure 2 (a), (b), and (c) below.

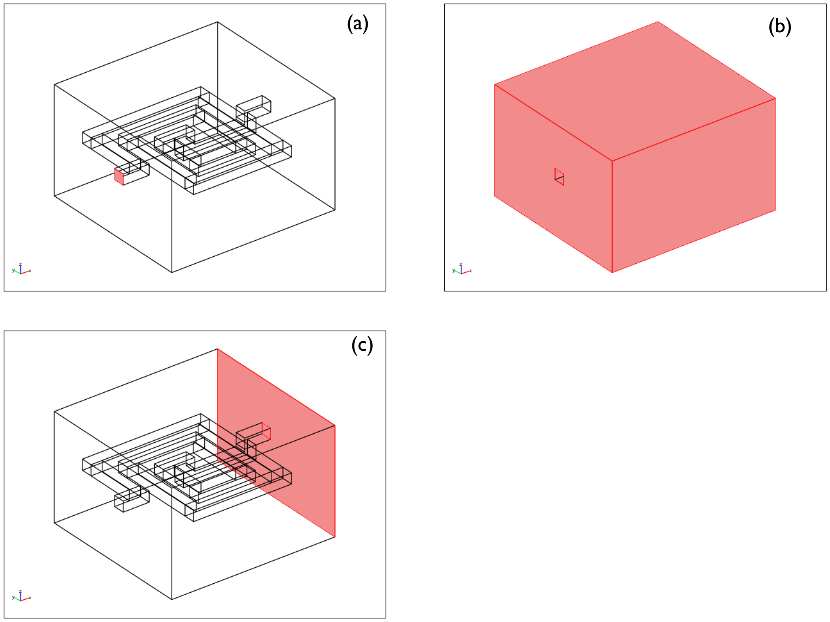

Figure 2: Boundaries with the same type of boundary conditions.

The boundary condition for the boundary highlighted in Figure 2 (a) is a magnetic insulation boundary with a terminal boundary condition. For the boundaries in Figure 2 (b), both magnetic and electric insulation prevail. The last set of boundary conditions, Figure 2 (c), are magnetically insulating but set to a constant electric potential of 0 V (ground).

Results

Figure 3 shows the electric potential in the inductor and the magnetic flux lines. The color of the flow lines represents the magnitude of the magnetic flux. As expected this flux is largest in the middle of the inductor.

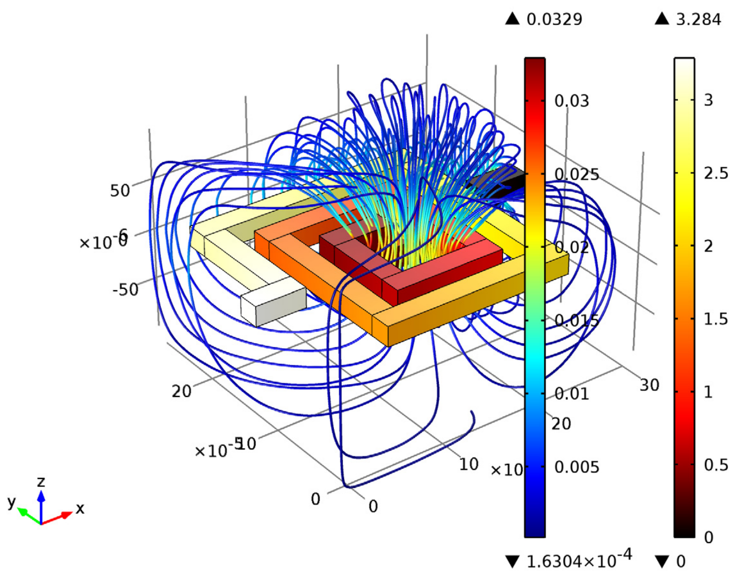

Figure 3: Electric potential in the device and magnetic flux lines around the device.

The model gives a self-inductance of $7.55 \cdot 10^{-10}$ H.

Model Library path: `ACDC_Module/Inductive_Devices_and_Coils/spiral_inductor`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click the **3D** button.
2 In the **Select physics** tree, select **AC/DC>Magnetic and Electric Fields (mef)**.
3 Click the **Add** button.
4 Click the **Study** button.
5 In the tree, select **Preset Studies>Stationary**.
6 Click the **Done** button.

GEOMETRY 1

Import 1

1 On the **Home** toolbar, click **Import**.
2 In the **Import** settings window, locate the **Import** section.
3 Click the **Browse** button.
4 Browse to the model's Model Library folder and double-click the file `spiral_inductor.mphbin`.
5 Click the **Import** button.
6 Click the **Wireframe Rendering** button on the Graphics toolbar.

This geometry would be relatively straightforward to create from scratch; here it is imported for convenience.

MATERIALS

Material 1

1 On the **Home** toolbar, click **New Material**.
2 Right-click **Material 1** and choose **Rename**.
3 Go to the **Rename Material** dialog box and type `Conductor` in the **New name** edit field.
4 Click **OK**.
5 Select Domain 2 only.
6 In the **Material** settings window, locate the **Material Contents** section.

7 In the table, enter the following settings:

Property	Name	Value
Electrical conductivity	sigma	1e6
Relative permittivity	epsilonr	1
Relative permeability	mur	1

Material 2

1 On the **Home** toolbar, click **New Material**.

2 Right-click **Material 2** and choose **Rename**.

3 Go to the **Rename Material** dialog box and type `Air` in the **New name** edit field.

4 Click **OK**.

5 Select Domain 1 only.

6 In the **Material** settings window, locate the **Material Contents** section.

7 In the table, enter the following settings:

Property	Name	Value
Electrical conductivity	sigma	1
Relative permittivity	epsilonr	1
Relative permeability	mur	1

Setting the conductivity to zero in the air would lead to a numerically singular problem. You can avoid this problem by using a small non-zero value. As 1 S/m is much less than the electric conductivity in the inductor, the fields will only be marginally affected.

MAGNETIC AND ELECTRIC FIELDS

Magnetic Insulation 1

In the **Model Builder** window, expand the **Component 1>Magnetic and Electric Fields** node.

Terminal 1

1 Right-click **Magnetic Insulation 1** and choose **Terminal**.

2 Select Boundary 5 only. To find Boundary 5, use the **Selection List** window.

3 In the **Terminal** settings window, locate the **Terminal** section.

4 In the I_0 edit field, type `1`.

Ground 1

1 Right-click **Magnetic Insulation 1** and choose **Ground**.

2 Select Boundaries 75 and 76 only.

This concludes the boundary settings. Note that the boundaries that you have not assigned are electrically and magnetically insulated by default.

MESH 1

Size

1 In the **Model Builder**, under **Component 1**, click **Mesh**.

2 In the **Mesh** settings window, locate the **Mesh Settings** section.

3 From the **Element size** list, choose **Coarse**.

4 On the **Mesh** toolbar, click **Build Mesh**.

STUDY 1

On the **Home** toolbar, click **Compute**.

RESULTS

Magnetic Flux Density Norm (mef)

The default plot shows the electric potential distribution in three cross-sections. There are plenty of other ways of visualizing the solution. The following instructions detail how to combine an electric potential distribution plot on the surface of the inductor with a streamline plot of the magnetic flux density in the air surrounding it.

3D Plot Group 2

1 On the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 On the **3D Plot Group 2** toolbar, click **Surface**.

3 In the **Surface** settings window, locate the **Coloring and Style** section.

4 From the **Color table** list, choose **Thermal**.

Data Sets

1 In the **Model Builder** window, expand the **Results>Data Sets** node.

2 Right-click **Solution 1** and choose **Add Selection**.

3 In the **Selection** settings window, locate the **Geometric Entity Selection** section.

4 From the **Geometric entity level** list, choose **Boundary**.

Selecting the boundaries of the inductor is can be done by first selecting **All boundaries** in the **Selection** list, then removing the exterior boundaries of the air box from the selection. Alternatively, click on the **Paste Selection** button and type `5–9, 11–74, 76`.

3D Plot Group 2

1 On the **3D Plot Group 2** toolbar, click **Streamline**.

2 Locate the **Streamline Positioning** section. From the **Positioning** list, choose **Start point controlled**.

3 In the **Points** edit field, type `3`.

4 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

5 In the **Tube radius expression** edit field, type `1e-6`.

6 Select the **Radius scale factor** check box.

7 Click to expand the **Quality** section. From the **Resolution** list, choose **Finer**.

8 On the **3D Plot Group 2** toolbar, click **Plot**.

The magnetic insulation condition on the exterior boundaries causes the field lines to bend and follow the contours of the box. This inevitably introduces a systematic error to the inductance computation. It would be possible to reduce this error by increasing the size of the box, or introducing an infinite element domain. Nevertheless, since the field is comparatively small near the surface of the box, the result is reasonably accurate already. Try visualizing the local magnitude of the field by having it decide the color of the streamlines.

9 Right-click **Results>3D Plot Group 2>Streamline 1** and choose **Color Expression**.

10 In the **Color Expression** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Magnetic and Electric Fields>Magnetic>Magnetic flux density norm (mef.normB)**.

11 On the **3D Plot Group 2** toolbar, click **Plot**.

Derived Values

1 On the **Results** toolbar, click **Global Evaluation**.

2 In the **Global Evaluation** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Magnetic and Electric Fields>Terminals>Inductance (mef.L11)**.

3 Click the **Evaluate** button.

The inductance evaluates to 0.755 nH.