Study of Resonant Coupling using Magnetic and Negative Refractive Index Materials

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Abstract: In this paper we simulate and study the effects of introduction of negative index refractive materials in a magnetic field. The structure and physical parameters of the material play an important role in the efficiency of energy transfer. The array, size and structure of the material have an important effect on the magnetic field distribution and coupling coefficients. Since the permittivity and permeability of the two media have different features, the component of the magnetic field changes when the observation point is moving towards the interface. This property and feature can be studied by optimizing the structure and position. The simulations are done using COMSOL a finite element analysis software. Interesting features are observed in the magnetic field distribution as we introduce the NIM.

Keywords: Negative Refractive index material, Magnetic flux density, Magnetic field

1. Introduction

Non contact charging of electronic equipment from mobiles to electric vehicle has created immense interest among researchers. There are various groups working on both radiative and non-radiative energy transfer. The idea based on strongly coupled magnetic resonances is of interest because of the increased distance of energy transfer.[1-3] This technology based on resonant magnetic coupling with the introduction of negative refractive index materials in the environment is also novel and exciting.[4-5] To improve the efficiency of wireless power transfer for low as well as high power applications it is important to understand the enhancement of magnetic flux density when the characteristics of the medium in which the power is transferred is changed. In this paper study of magnetic flux density with and without the negative refractive material is simulated and analyzed. We present results that show enhanced magnetic flux field concentration by varying the size and position of the NIM.

2. Theory

The magnetic flux density denote the presence of a magnetic field in a given region of space related to the magnetic field intensity by

$$\vec{B} = \mu \vec{H}$$

(1)

where **B** is the magnetic flux density in Tesla, **H** is the magnetic field intensity in A/m and μ is the permeability of the medium, H/m.

The magnetic field H at any point in space to the steady current, I that generates H is given by Biot-Savart law[6]

$$d\vec{H} = \frac{I d\vec{l} \times \hat{R}}{4\pi R^2} \text{ A/m}$$

(2)

where $\vec{R} = \hat{R} R$ is the distance vector between dl and the observation point.

To enhance the magnetic flux density it is desired to change the value of permeability by selecting the material which has high relative permeability

$$\mu_r = \frac{\mu}{\mu_0}$$

(3)

where μ_0 is the magnetic permeability of free space. The magnetic flux density can also be made to concentrate at any desired place by introducing a negative refractive index material (NIM). The NIM has both the permeability and permittivity (ε) equal to -1. This material when introduced between the source of a magnetic field and receiver enhances the energy transfer range. To understand the behavior of NIM in a uniform magnetic field, simulation environment can be based on the FDTD (Finite Difference Time Domain) or the FEM (Finite Element Method). In both cases, the Maxwell equations are solved for each element within the boundary conditions by dividing the structure into a finite number of elements. To solve using FEM the following Maxwell equations are to be solved for each element

$$\nabla \times H = J$$
$$B = \nabla \times A$$
$$B = \mu_0 \mu_r H$$

(4)

And the boundary conditions as stated below:

$$B_{1n} = B_{2n}$$
$$H_{1t} = H_{2t}$$

(5)

where A is the magnetic vector potential, B_{1n} and B_{2n} are the normal component of magnetic flux density at medium 1 and medium 2 respectively. Similarly H_{1t} and H_{2t} are the tangential component of the magnetic field intensity at medium 1 and medium 2, respectively. Figure 1, shows the schematics of the source and the receiver with respect to the NIM. In this study we will simulate the magnetic field profile in the source half of the diagram, wherein we will be introducing the NIM structure. The receiving coil will be placed at the optimized position in the magnetic field profile.
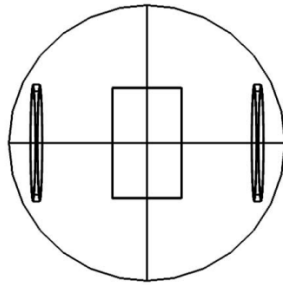

Figure 1. Source and Receiver position with respect to NIM.

3. Use of COMSOL Multiphysics

3.1 Model

A geometric model is created in COMSOL with the following considerations:
A circular coil carrying a current of 1 A, radius 100mm and wire thickness 2mm. To analyze the magnetic flux profile, a 2D axisymmetry space dimension and magnetic field physics are considered. The geometry for the above considerations is shown in figure 2. The boundary for this model is extended up to infinity. COMSOL provides infinite element domain for this purpose. The infinite element of 50 mm was used for our simulations.
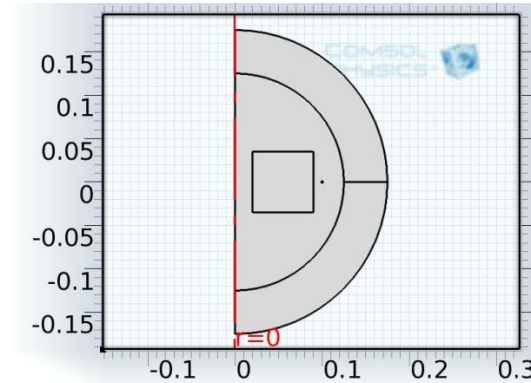
Figure 2. Geometry of coil with negative refractive index material.

3.2 Simulation results

The magnetic flux density analysis was done for DC and AC frequencies of 1 MHz and 1 GHz and the field profiles are shown in Figure 3. Appreciable change in the field profile is observed for 1 GHz frequency whereas no change is seen when we go from DC to 1 MHz frequency. Also for AC frequencies there is field exclusion within the coil. The deviation at 1 GHz frequency, maybe due to the selection of the boundary and/or the infinite element dimension. This is being investigated.

When a NIM is introduced in the medium near the coil, variation in the magnetic flux profile (density) is observed. Figure 4, presents the variation in magnetic flux profile with the introduction of the NIM. This figure shows what happens to the magnetic flux density when we change the dimensions of the NIM. The study was made by fixing the width to a constant value of 70mm and increasing the height of the NIM from 10mm to 70mm. Then, keeping the height at a constant value of 70mm and reducing the width from 70mm to 10mm. We observe concentration of the flux density at various regions in space. This concentration tends to move away from the source, as the area of the NIM increases. In order to reduce the total area of NIM, an array of 4 element of size 10mm x 70mm is introduced instead of a single block.

Figure 5, presents the magnetic flux profile for various distances from the sources and the array. The distance between the elements in the array is kept at a constant distance of 10mm. As seen in Figure 5, when the distance between the source and the elements is 10mm, the flux density at the outermost element is almost the same as that of the source. The

distance from the source to the outermost element is 80mm. This focus seems to be disturbed when we move the array away from the source or towards the source. We have also change the number of elements in our array from 0 to 4. This observed flux profile is shown in Figure 6. We observe that as we increase the number of elements from 0 to 4 we get a concentration of the flux field at the outer of the 4th element, 80mm from the source. The same phenomenon is observed when we increase or decrease the space between the NIM elements. This is shown in Figure 7.

4. Conclusion

The simulation result shows that the magnetic field can be focused on a particular region by varying the size and structure of the NIM. The spacing between the NIM and distance between the NIM and excited coil play an important in this process. These parameters play a vital role in enhancing the magnetic flux density at specified regions in the field space.

By placing a receiver coil at the focused flux regions we will be able to enhance the pickup. This increase in the field gives rise to increase in induced voltage. This can be achieved if the source coil is excited with an AC. Further, to enhance the range and efficiency we can use resonators in both the source and the receiver. The analysis can be done by optimizing the structure and dimensions of elements. Further work need to be carried out with different nano structures.
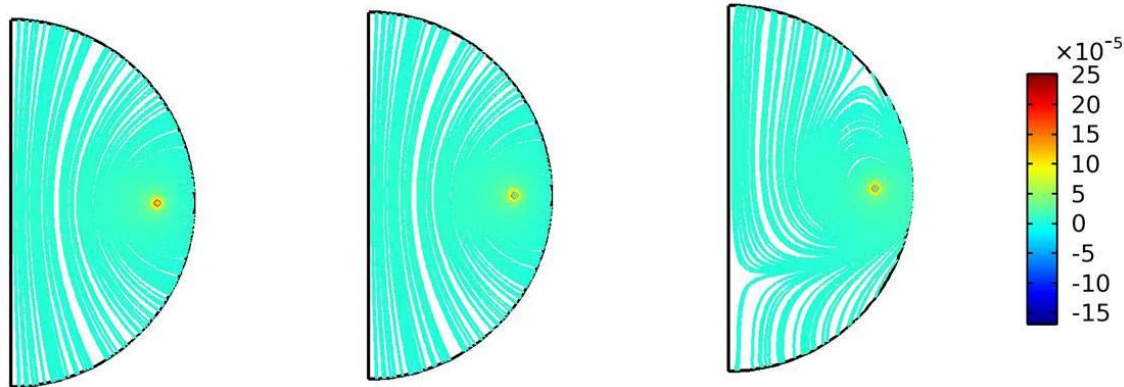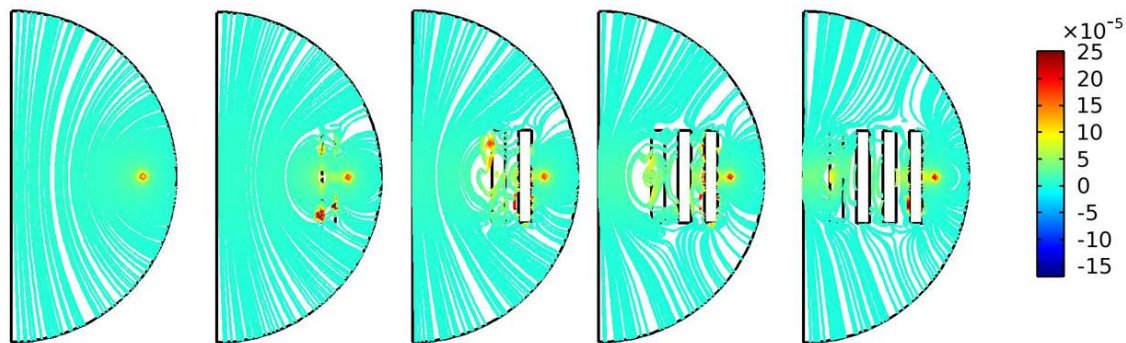

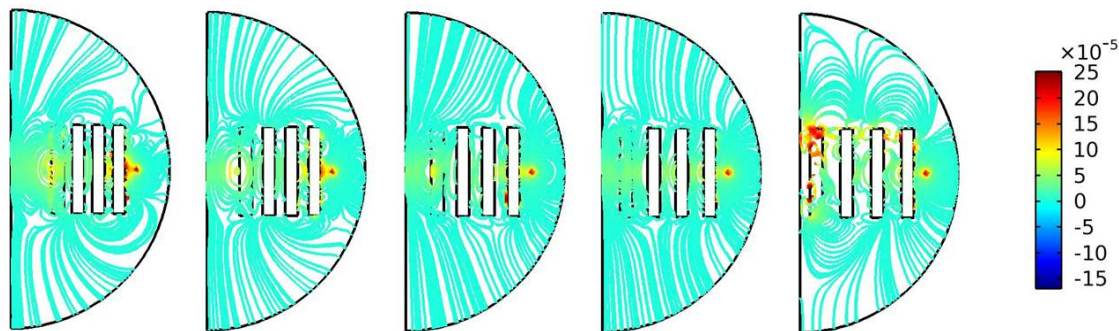**Figure 3**. Magnetic flux density at DC, 1 MHz and 1 GHz (Units - Tesla).
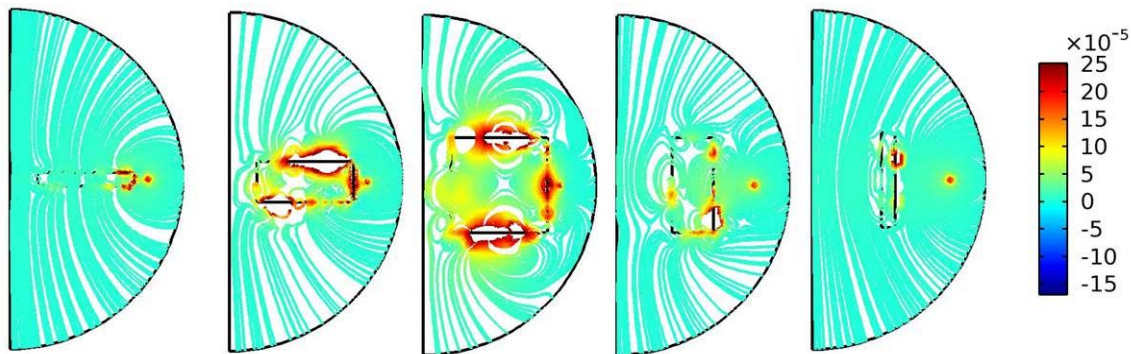
Figure 4. NIM of varying size from 10 x 70, 30 x 70, 70 x 70, 70 x 30 and 70 x 10 mm (Units - Tesla).
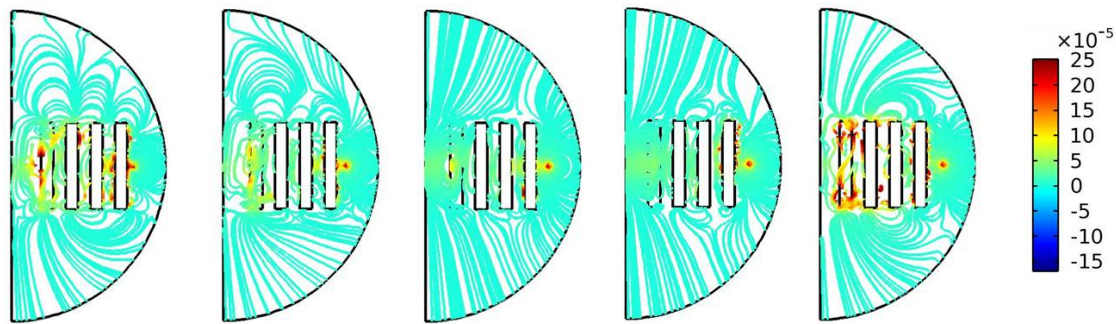
Figure 5. Spacing from the coil to the first NIM is varied from 6mm to 14mm in steps of 2mm (Units - Tesla).

Figure 6. Magnetic Flux Density variation without NIM and with 1, 2, 3, 4 NIM respectively (Units - Tesla).

Figure 7. Interspacing between the NIM varied from 6mm to 14mm in steps of 2mm (Units - Tesla).

5. References

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6. Acknowledgements