Figure 1. Caption?

FYP

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Abstract.

1. Introduction

$$y = x \tag{1}$$

1.1. Maxwell equations

1.2. Transformation Optics and Metamaterials

2. Methods

2.1. DC Magnetic Fields

Helmholtz coils were powered by a constant DC current to create a uniform magnetic field within their center. A commercially available XXX Hall probe was zeroed by using a MuMetal cannister, and then placed at the center of the Helmholtz coils. A Hall probe relates a measured Hall voltage, V_H, to a surrounding magnetic field, B [**?**] as

$$V_H = \frac{IB}{net}. \tag{2}$$

The probe maintains constant current supply I, and material paramaters n (charge carrier density), e (charge of electron) and t (thickness of probe) meaning a calibrated probe may give accurate readings for magnetic fields.

The magnetic field, B, produced at the center of Helmholtz coils with radius R, seperated by a distance R should follow,

$$B = \frac{8}{5\sqrt{5}} \frac{\mu_0 n I}{R}, \tag{3}$$

where I is the current supplied to the coils and n is the number of turns of wire. This equation follows directly from the Biot-Savart law [**?**] and the relative geometry of the coils as seen in figure **??**. From equation 3 it can be seen that the magnetic field should increase linearly with supplied current. Using the Hall probe we ensured this was the case and found the relationship of current supplied to magnetic field produced for our paticular Helmholtz arrangement.
Now, with the capability to produce known external magnetic fields, the described field concentrating shells may be placed within this field and the Hall probe may be placed within their inner radius to measure concentrated field.

Figure 2.

2.2. AC characterization

Initially the Helmholtz arrangement was repeated for exploration of the concentrating shells behaviour in alternating magnetic fields. However, instead of a Hall probe, a small solenoid was used to detect the oscillating field. From Faraday's law, a voltage will be induced in a wire loop due to a time dependent magnetic field. A series of loops constituting a small solenoid will respond to a sinuisoidal magnetic field, $B = B_0 \cos wt$, with the relationship,

$$V = -NAB_0\omega \sin \omega t, \tag{4}$$

where A is the area of one loop and N is the number of loops, ω is the angular frequency of the alternating magnetic field and t is time.
As ω is known and all other parameters except external field are kept constant, the voltage across the solenoid may be measured experimentally to find the relative magnetic field strength.
The solenoid must however be characterized in order to find the absolute magnetic field values. This was done by measurement of the self inductance, L, of the solenoid as, XXX

$$L = \mu_0 \mu_r N^2 A/l \tag{5}$$

XXX

Due to the induced voltage across the inductor being small and background noise being high, a lock-in amplifier was used to select only the desired signal frequency. This substantially reduced noise in our readings allowing higher frequency and lower magnetic field strength experiments.

Use of solenoid, limitations of Helmholtz and pick up. Use of RLC circuitary.

3. Results

3.1. DC Magnetic Fields

Using the DC Helmholtz set up as described in Methods, we observed constant concentration factors for different shell constructions in an external magnetic field ranging from 1 to $22G$. No shell, 18 MuMetal, 36 MuMetal, 18 Copper and 18 MuMetal + 18 Copper shells were used and their behaviour with field may be seen in figure **??**.
It was found that the shell contruction of 36 MuMetal thin sheets gave the optimum concentration of $C = 2.38$ with minimal error (0.1%) at higher field strengths and a maximum error of 4.0% at an external field of 1.4 G. This increase in error at low magnetic fields is due to limited sensitivity of our Hall probe and current measurements over the Helmholtz coils.
Similar error relationships are observed for the other constructions. It should be noted that we assume the dipole has been placed in the same position and orientation in all experiments and so errors due to placement are excluded here.
The copper only shell showed no concentration of internal field as expected. This is due to copper having a relative permeability similar to air, $\mu_r = 1.0$, and so negligible field guiding properties. Furthermore, in the DC regime copper will not shield XXangularXX fields as required by the optimal TO concentrator.

3.2. AC characterization

The Helmholtz coils were supplied with an alternating current in order to create an alternating magnetic field. Now using the voltage induced across solenoid to detect alternating magnetic field strength

Figure 3.

as decribed in Methods, the concentration of various shell arrangements were explored.

The concentration factors between 0.5 and 30 kHz can be seen in figure **??**. It was found that a mixed shell of alternating 18 copper and 18 MuMetal sheets had the optimum concentration factor of $C = 3.12$ at 5 kHz.
Here we can see that the copper sheets now have some concentrating effect as frequency increases. This behaviour is expected as copper will shield perpendicular alternating magnetic fields which is desired for the optimal TO concentrator. However, it is suprising that this shielding occurs at such low frequencies, i.e. Much less than skin depth of copper.XXX

The strong linear decay of field concentration after 5 kHz for all but the copper only shell is also a suprising result which, although could be explained by the MuMetal permeability frequency response, also appears to occur at too low a frequency.

Apart from instrument and measurement reading errors which constitute only a small error (XXX%), we observed errors due to high pick-up in cables connecting the solenoid to the lock-in amplifier. This source of noise was at the same frequency as our desired signal and so is difficult to remove other than careful cable placement and using shielding. We believe this pick-up was worsened by the fact the Helmholtz coils must be driven with high voltage and current to create a useful magnetic field and that the magnetic field was not localised to just our solenoid and shell but also was subject to the cabling and any nearby detectors. This prompted a decision to focus on two dipole coupling experiments as this pick-up error can be greatly reduced.

3.3. Power transfer

3.4. Other COMSOL

4. Discussion

5. Conclusions

6. References