Magnetic microscopy/metrology potential of metamaterials using nanosized spherical particle arrays

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ABSTRACT

Techniques for imaging and characterizing magnetic samples have been widely used in many areas of research involving magnetic materials. Nowadays, magnetic microscopy techniques play a critical role in characterizing magnetic thin film structures. In considering the various techniques, optical techniques offer some unique advantages over alternative techniques (e.g. MFM), as they are least affected by magnetic noise and, for the same underlying reasons, have also proven to be more suitable for "high speed" magnetization measurements of magnetization dynamics, which are increasingly important in many of today's research scopes.

At the same time, development of metamaterials are opening the doors for newly behaving materials, such as those demonstrating negative refractive index, potentially useful in a variety of applications, such as imaging. Metamaterials deploying arrays of silicon particles, and even alternating silicon particles and split ring resonators have recently been shown to demonstrate interesting behavior, such as negative magnetic susceptibility and large resonant peaks in the Terahertz regime. Such high frequencies offer the potential bandwidth of extraordinarily fast dynamics, which are increasingly being generated in magnetic materials, for example, in optically-induced demagnetization and all-optical magnetic recording.

Here, initial investigations toward ultra high-speed imaging and/or information extraction from magnetic samples is discussed considering metamaterials deploying mainly spherical particle arrays. In addition to the frequency spectrums of the system, the response of the system to external magnetic fields and background permeability changes due to external fields are investigated. Our results suggest a significant potential of metamaterials for use in probing information from magnetic materials.

Keywords: metamaterial, magnetic microscopy, magneto-optic imaging.

I. INTRODUCTION

Recent efforts in science and engineering to reduce the length scales of the systems that are being investigated have led to new observations that offer both new insights into scientific phenomena as well as into new possibilities. In the area of optics, this observation is, perhaps, most cogent in the development of tailored materials known as metamaterials. Metamaterials are artificial materials that are designed or engineered to give rise to effective material properties that are otherwise, difficult to observe. Producing properties such as negative refractive index [1] and negative magnetic permeability [2] are two examples of some achievements using metamaterials. Another feature that has been demonstrated both theoretically and experimentally, and of particular interest here, is the presence of resonant behavior in some metamaterials at wavelengths that are also rare in nature, in the terahertz regime and beyond. In principle, with resonance frequencies f_r in the range of $f_r > 10^{12}$ Hz suggests such a system which may be made to interact or be coupled with another system whose dynamics is sufficiently slow and constitutes a way to extract information from the dynamic or coupled system should it alter the behavior of the metamaterial. This is the direction of this work, to investigate the potential of interacting with a metamaterial, a magnetic system, to explore effects on the behavior of the metamaterial.

Interestingly enough, in some areas of magnetism, recent years of investigations have also revealed interesting behavior when magnetic systems have been made to interact with light. One example is optically induced demagnetization [3-5], where a light source is shone onto a magnetic thin film sample and ultrafast dynamic changes in the system are observed that are on the order of several pico (10^{-12}) and remarkably down to as fast as several femto (10^{-15}) seconds. It has been demonstrated in several materials such as Ni, CoPt, and GaMnAs. In each of these cases, the process is thermal and results from efficient and rapid fluctuations of the local magnetic moments in the sample incited by the energy of the laser source. Another example, and maybe more significant, is the process of all optical magnetic recording where a circularly polarized laser source is also shone onto a magnetic sample (usually a rare-earth alloy like Gd(Tb)Co) and through a process known as the inverse Faraday effect, controls the bistable states of the magnetic layer, enabling control in either the 'up' or 'down' state [6-7]. This may be useful in applications like data storage and research work is indeed, underway, to explore the feasibility of this option. While these systems demonstrate remarkable dynamics, this limits the number of tools that may be used to study these kinds of systems, which is essential to further develop these kinds of mechanism. So far, only optical methods using pump-probe techniques, deploying the Kerr effect, have been successfully used to extract information on the average magnetization at an instance of time. But other systems often used to extract information from magnetic systems such as induction methods, vibrating-sample methods, force methods such as MFM, are not possible candidates in the dynamic range of interest as their bandwidths are too low. Thus, it is important to look towards new ways to investigate the kind of ultrafast systems mentioned here, hence an interest in the properties of metamaterials towards fulfilling a potential role in the metrology and since we are also considering particle arrays, one may even say microscopy of magnetic samples.

II. RESULTS AND DISCUSSION

One of the first analyses needed is to determine the properties for a metamaterial that may be suitable for the systems of interest, which means that the system of spherical particles must have a bandwidth capable of responding to picosecond or faster timescales. For the frequency spectrum of a spherical particle, using the MIE solution, which is a solution to Maxwell's equation in the particular case of a spherical particle in the presence of an incident plane wave as shown in Fig 1, the extinction can be computed in a absence of any external magnetic field to examine which systems lead to resonant responses in THz frequencies or even faster. Fig 1 shows wavelength (frequency) spectrum results computed from the MIE solution using a silicon particles of radius 65nm, and for comparison, a silver particle.

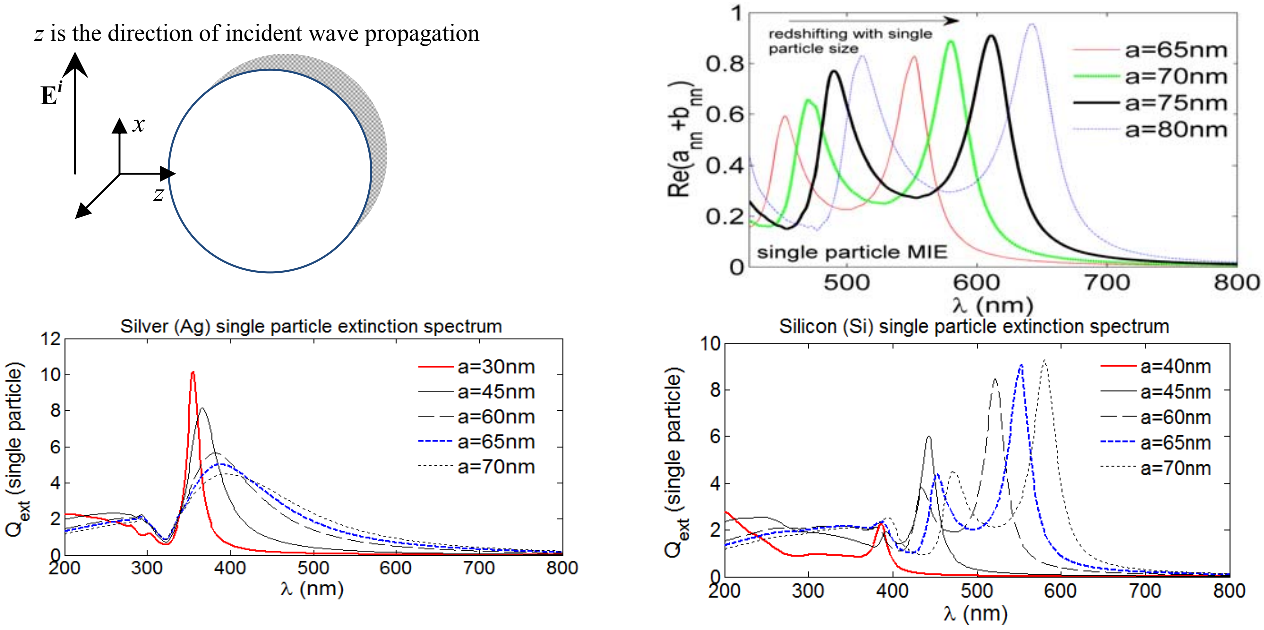


Figure 1. Top left: diagram illustrating the assumed situation for the single particle MIE solution. Top right: illustrates the sum of the MIE coefficients representing both electric and magnetic contributions, showing redshifting (to larger wavelengths) with increasing particle size. Bottom: extinction spectrum computed for silver (Ag) and Silicon (Si) particles also towards smaller particle sizes illustrating resonance peaks in the range of interest.

It is clear from the MIE solution that even a single particle with radius a few tens of nanometers generates resonant peaks at wavelengths of a few 100 nm (in the PHz range), which is sufficient for the systems of interest and such sizes are very feasible for fabrication.

There are a variety of metamaterials that can generate a spectrum similar to that shown in Fig 1, and so one has to resolve further which among them is most suitable for fast dynamics in magnetic systems. Based on experimental work that has been done in the past [8], an emphasis here is placed on dielectric materials, rather than metals. It has been shown that one of the advantages is lower losses, and this has been shown to contribute to stronger resonance peaks [8]. Thus, Si particles are considered primarily in the remaining calculations.

Beyond the MIE theory, it is also of interest to investigate an array of these particles, however, one must do so in a way that allows the introduction of an external (static) magnetic field. One of the simplest ways to get information from such a system is to use the so-called coupled electric and magnetic dipole (CEMD) method, which simply assumes each particle to be a dipole and computes the total field at each particle. From this process, one constructs a linear set of equations, and this allows the addition of a static magnetic field within such a formulation. The CEMD method equations with an added magnetic field are given by [9]

$$\mathbf{d}_i = \boldsymbol{\alpha}_i^e \mathbf{E}_i^0 + \sum_{j=1, j\neq i}^{N} \boldsymbol{\alpha}_i^e \left[\hat{C}_{ij}\mathbf{d}_j - \sqrt{\frac{\mu_0}{\varepsilon_0}}\,\hat{G}_{ij}\mathbf{m}_j \right] \tag{1}$$

$$\mathbf{m}_i = \boldsymbol{\alpha}_i^m (\mathbf{H}_i^0 + \mathbf{H}_e) + \sum_{j=1, j\neq i}^{N} \boldsymbol{\alpha}_i^m \left[\hat{C}_{ij}\mathbf{m}_j - \sqrt{\frac{\mu_0}{\varepsilon_0}}\,\hat{G}_{ij}\mathbf{d}_j \right] \text{ where} \tag{2}$$

$$A_{ij} = \frac{\exp(ikr_{ij})}{r_{ij}}\left(k^2 - \frac{1}{r_{ij}^2} + \frac{ik}{r_{ij}}\right),\ B_{ij} = \frac{\exp(ikr_{ij})}{r_{ij}}\left(-k^2 + \frac{3}{r_{ij}^2} - \frac{3ik}{r_{ij}}\right),\ \hat{C}_{ij} = A_{ij}\hat{I} + B_{ij}(\mathbf{n}_{ji} \otimes \mathbf{n}_{ji}),\ i \neq j$$

$$D_{ij} = \frac{\exp(ikr_{ij})}{r_{ij}}\left(k^2 + \frac{ik}{r_{ij}}\right),\ \hat{G}_{ij} = D_{ij}\mathbf{n}_{ji}\times,\ i \neq j \qquad \text{(3a-e)}$$

$\mathbf{d}_i$ and $\mathbf{m}_i$ are the electric and magnetic dipoles at x_i. $\alpha_{\mathrm{e(m)}}$ are the electric (magnetic) polarizabilities; r_{ij} is the distance between i^{th} and j^{th} particle (acting as a source) [9,10,11]. Figure 2 shows that in the absence of an external field, the calculated extinction spectrum of the single particle and the array agree well.

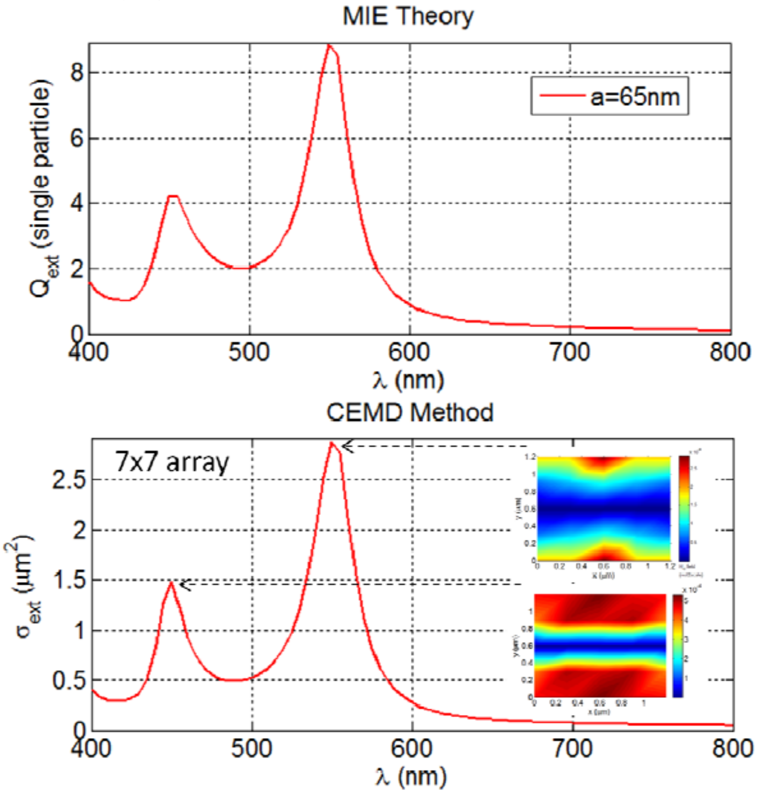


Figure 2. Top: diagram illustrating the assumed situation for the single particle MIE solution. Bottom: extinction spectrum for an array according to the CEMD method. Inset figures in the bottom illustrate different distributions at different wavelengths. For all calculations, the system is Si of 65 nm radius.

Figure 2 (bottom) which shows results from an array also shows that each of the resonant peaks correspond to different dipole distributions (or modes) for the array. This observation is essential in order to make use of this formulation for our interests. This is because the equations that are given for the extinction, scattering, etc. in the CEMD (and MIE) method are generally, not appropriate for this problem of introducing an external magnetic field [12], and thus cannot be used here. However, an indirect method, which *is* used here, is to see if the distributions or modes of the particle array are affected. If there is a change in the mode in this array, it can be inferred that there is likely a change in the spectral response. To more clearly show the modal-wavelength correlation, Figure 3 shows dipole modes, where an array of 17 x 17 Si particles is used to compute the magnetic dipole distributions at two wavelengths, 650nm (left) and 450 nm (right).

Figure 3. Left: Magnetic dipole modes (x,y,z) for λ = 650 nm Right: Magnetic dipole modes (x,y,z) for λ = 450 nm. Note: Units of my are arbitrary.

An alternative way to describe this observation is that the system does not develop an invariant distribution whose amplitudes are altered synchronously across various wavelengths maintaining the same distribution, but rather sets up modes in accordance with the wavelength, in this case. Figure 4, then, shows how the modes are affected by the presence of an external dc magnetic field $\mathbf{H}_e$.

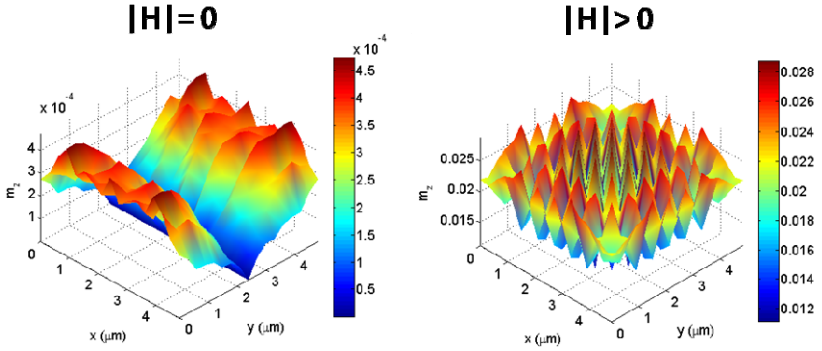
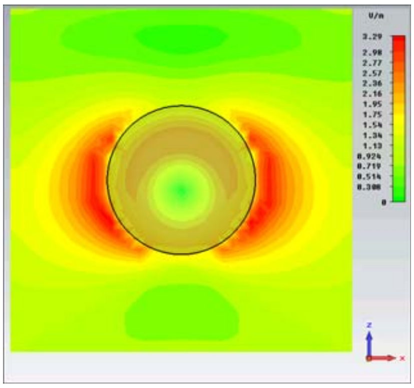


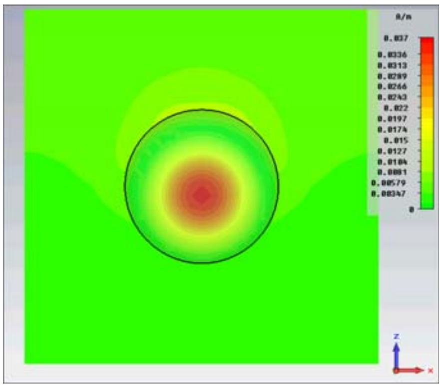
Figure 4. *z* component of the magnetic dipole with (left) and without (right) external magnetic field along the z direction. The presence of the dc field is seen to affect the distribution/mode of the Si particle array.

The presence of the external magnetic field $\mathbf{H}_e$ (applied along the *z* direction) affects the modes of the 17 x 17 array of Si nanoparticles of radial size 65 nm. This observation that the modes change with the field indirectly suggests there should also be some change in the frequency response to the system.

Thus far, the results suggest that the metamaterial consisting of nanometer sized particle arrays should have a spectral response that is affected very noticeably by the presence of an external magnetic field. This, therefore, suggests there is some potential of such systems to extract information from magnetic systems.

Another possibility considered here is embedding the Si particle array in a permeable medium, with a permeability that changes with the external field. This problem is solved using a finite element software package to compute the field distributions within a single embedded particle. Figure 5 shows results for three different values of the magnetic permeability in the surrounding medium, at μ=1, 10, and 100.





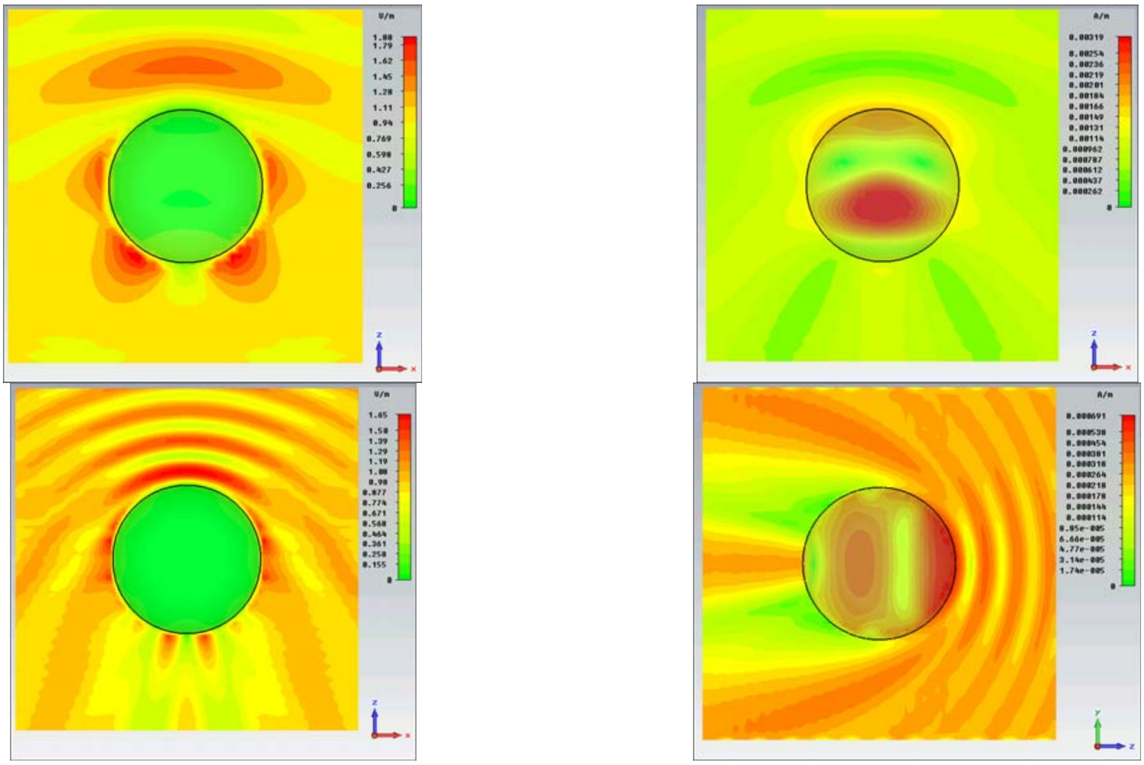


Figure 5. Top left: 65 nm Si particle response to the variation in magnetic permeability of the medium. Left side show electric field (units of E are amplification relative to input field amplitude). Right side shows magnetic field amplitudes (in arbitrary units). The 1st, 2nd, and 3rd rows show cases of μ=1, 10, and 100 respectively.

By embedding the particle in a permeable medium, the response is also affected by this change in μ. The result in this change is to also influence the field inside the Si particle. The general trend is that higher order modes become present in the system. For example, in μ=1, the particle's electric field is mostly an electric dipole, however, for μ=10, a quadrupole is present. The presence of such higher modes gives rise to changes in the spectrum, leading to more 'peaks' in the spectrum. Figure 6 shows data points from the extinction cross section, where the first plot is for reference, computed for a single particle with air surrounding. This first calculation also agrees well with the calculations using MIE and also the CEMD method (Figure 2).

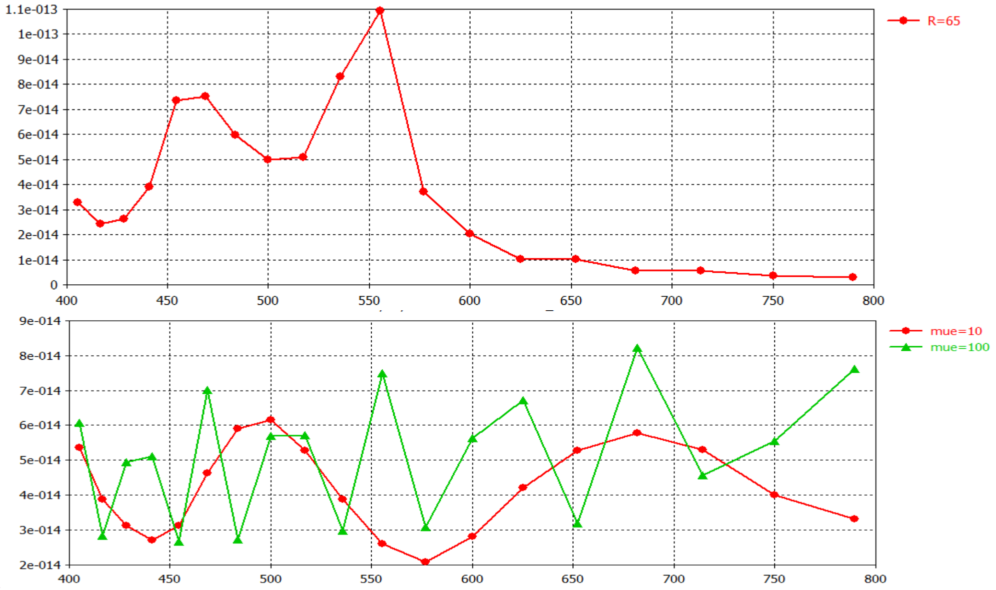


Figure 6. Top: Computed extinction cross section for a Si particle embedded in a permeable background material, thus μ changes with an external magnetic field (generated using CST).

For the cases of a permeable surrounding medium, the spectrum simple shows more peaks, corresponding to the higher order modes found in the system, as illustrated in Figure 5. Thus, it is also seen that in this situation, strong affects on the frequency response of the system are possible if the permeability is changed due to the presence of an external field.

III. CONCLUSION

In conclusion, the potential of using arrays of Si nanoparticles in a metamaterial has been investigated using MIE solution, the CEMD method to probe the dipole mode interactions with an external field, as well as introducing a permeable surrounding medium that responds to the presence of an external magnetic field have been explored. The results obtained suggest favorably there is an significant affect on the system response and therefore suggests that further steps may be wise in further considering metamaterials for applications in microscopy and/or metrology of magnetic systems.

IV. REFERENCES

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