Light Transport in Magnetic Colloids: A Review

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Abstract- Transportation of light through magnetic colloids has become field of interest due to its wide range of applications in the field of science and engineering. Optical properties of light are significantly changed when light propagates through the magnetic colloidal suspension which is also referred as magnetic fluid or ferrofluid. Magnetic colloid is a fluidic material of very fine (~ 8 to 10 nm) magnetic particles dispersed in a proper liquid carrier. We review some optical effects observed in magnetic colloids in presence of external magnetic field with some theoretical models and its applications in various fields of science and engineering. We have also reviewed the optical properties for Bi-disperse magnetic colloids.

Keywords – Bi-disperse ferrofluid, Optical transport, Magnetic carriage, Mie scattering

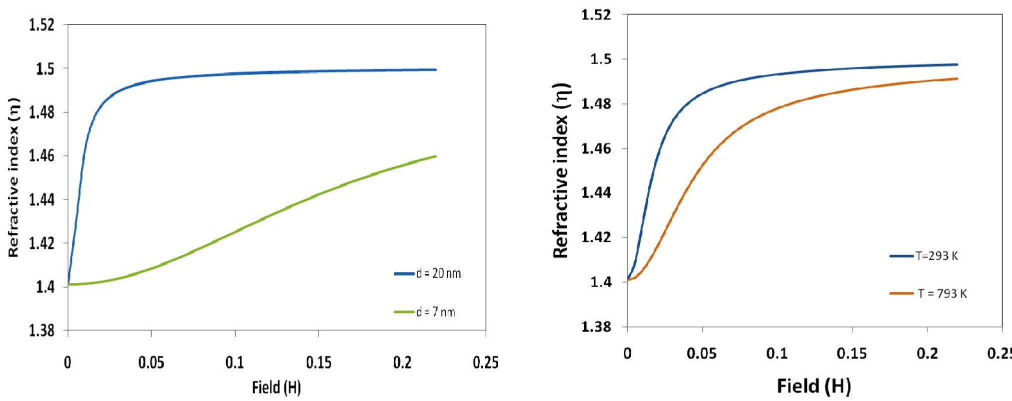
I. Introduction

Magnetic Colloid (MC) which is also known as Magnetic Fluid (MF) or Ferro-fluid (FF) is an advance colloidal material composed of nano sized magnetic particles dispersed in a homogeneous liquid medium [1-3]. Magnetic nano particles can be prepared by the method of size reduction [4] or chemical precipitation [5]. To avoid agglomeration between two magnetic particles, they have to be coated with proper material called surfactant. Based on nature of surfactant magnetic colloids are classified into two groups: Surfacted Magnetic Colloids and Ionic Magnetic Colloid. Surfacted Colloids are formed by magnetic particles (usually magnetite, Fe_3O_4) coated with surfactant agents (amphiphilic molecules, as oleic acid and aerosol sodium di-2 ethylhexyl-sulfosuccinate) in order to prevent their aggregation [1]. In ionic ferrofluids [6, 7], nanoparticles are electrically charged to keep the colloidal system stable.

Light transport through magnetic colloids is strongly influenced by external magnetic field due to the formation of linear chains or rods along the field direction at low particle concentration and complex structures such as columns, labyrinthine pattern at high particle concentration. During the transportation of light magnetic colloids show different magneto optical properties like birefringence, linear dichroism, Faraday rotation, Faraday ellipticity and circular dichroism [9–11]. Light scattering studies by magnetic colloids has shown some interesting photonic properties [12-15]. Recently, Magnetic Colloid based optical devices have been proposed and established, for instance, Magnetically tunable optical gratings,[16-17] optical switch,[18-19] optical modulator, [20–23] optical capacitor,[24] optical limiters, [25-26] and sensors.[27–31]. Therefore, Magnetic Colloid is the best suitable nanoelectrochemical system, if one wants to engineer a novel device with desirable optical properties. The range of applications and fascinating properties of Magnetic Colloids motivated us to pursue this study.

II. Magnetic Tuning of Refractive Index

It was observed that in presence of external magnetic field, the refractive index of the ferrofluid changes because of the magnetically induced structure formation. [32] It was reported that the refractive index of magnetic fluid (η) increases with the external magnetic field and saturated for higher field. [33] For small particle size (typically less than 10 nm) the transmitted intensity increases with external magnetic field but decreases for the particle size greater than 10 nm. This is due to effects of van der Waals and magnetic dipole-dipole interaction. [34] In our recent work, the variation in refractive index with temperature and particle size was studied. [35] For magnetic colloidal suspension entire anisotropy in light transmission can be explained based on the structure formation in presence of external magnetic field and governance of dipole – dipole interaction over van der Waals interaction. We have considered field dependent refractive index as $\eta = \eta_0 + \eta_\infty F(\alpha)$; n_0 is the refractive index of the ferrofluid at zero field, n_∞ is the refractive index of the ferrofluid at an infinite field (saturation value), $F(\alpha) = \alpha L^2(\alpha)/\alpha - L(\alpha)$, $L(\alpha) = \coth \alpha - \alpha^{-1}$, $\alpha = \mu H/k_B T$, μ is magnetic moment and, H is applied field, k_B is Boltzmann constant and T is absolute temperature. $F(\alpha)$ is derived using effective field medium. [36] It is observed that refractive index tends to saturate "early", when the particle size is large and temperature is low. The refractive index saturates for large field when particle size is reduced below 10 nm. The magnetic field required to saturate refractive index is also changed when we change temperature of the system. Fig. 1 shows the refractive index response to the magnetic field for (a) different particle size and (b) different temperature.



(a) (b)

Fig.1. (a) the variation in refractive index (η) of particles of two different diameters (7 nm and 20 nm) as a function of magnetic field at constant temperature of 300 K and (b) variation in refractive index (η) of particle (diameter = 15 nm) at different temperatures, i.e. 293 K and 793 K with magnetic field.

However the chain formation is not possible in case of bidispersed magnetic colloids in which micrometer sized magnetic particles are dispersed in magnetic nano fluid. The variation in refractive index due to field induced structure formation may not be possible when particle size is more (of the order of micrometer). The modulation in refractive index for such colloid can be explained on the basis of magnetically modulated dielectric constant (ε). The refractive index is given by, $n = \sqrt{\varepsilon}$, $\mu = 1$ at optical frequency and ε can be tuned by the external magnetic field. [37-38] Light transport through bidispersed magnetic colloid is affected by changing refractive index of scatterer. The change in refractive index of the bidispersed colloid (η) with external magnetic field (H) is studied for different temperature and various particle size of scatterer. We have considered a bidispersed FF, which is suspension of nanomagnetite with suitable surfactant in suitable carrier like kerosene or water in known volume fraction (approx. $10^{15}/m^3$) in which micron size particle of known volume fraction (approx. $10^5/m^3$) are suspended. We have considered field dependent refractive bidispered FF as $\eta_s = \sqrt{\varepsilon}$ where $\varepsilon = \varepsilon_0 + \varepsilon_\infty F(\alpha)$; ε_0 is the dielectric constant at zero field, ε_∞ is dielectric constant at an infinite field (saturation value), $F(\alpha) = \alpha L^2(\alpha) / \alpha - L(\alpha)$, $L(\alpha) = \coth \alpha - \alpha^{-1}$, $\alpha = \mu H/k_B T$, μ is magnetic moment which is 5.652×10^{-19}, H is applied field, k_B is Boltzmann constant and T is absolute temperature and wavelength of light is taken as 633 nm. Light transport through Bidispersed colloid is affected by changing refractive index of scatterer (η_s). The relative refractive index (ξ) can be calculated by taking ratio of refractive indices of scatterer (ηs) to the fluid (η). We choose three different values of refractive index for scatterer as ηs = 3, 4 & 5. From above mentioned formula ξ was calculated. Graphs of ξ versus external magnetic field are shown in fig.2 (a), (b) and (c)..

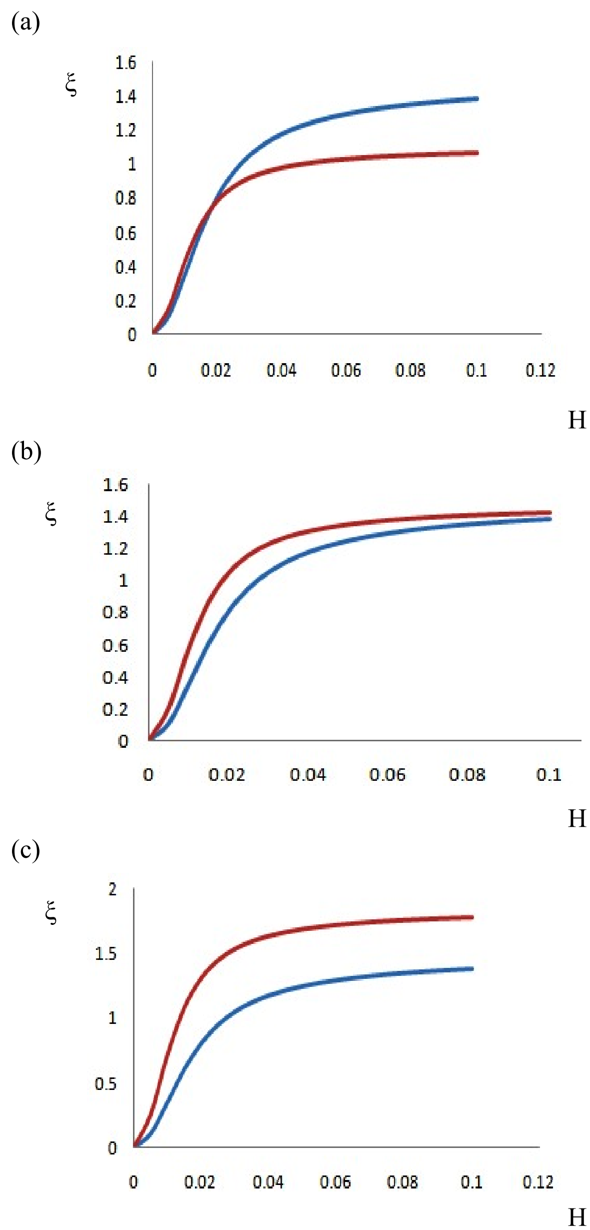


Figure 2. The variation in relative refractive index (ξ) with external magnetic field (H) for (a) $\eta_s = 3$ (b) $\eta_s = 4$ (c) $\eta_s = 5$. The red line shows change in η and blue line shows the change in η_s

A probable reason for the modulation of ξ is extinction of light. The magnetic modulation of ξ was discussed based on Magnetic Mie resonance, Optical limiting and magnetic hole theory. [39] Out of all probable reason for the magnetic tuning, we found that the most appropriate one is the Magnetic Mie resonance, in which the dispersed magnetic micro spheres will act as Mie scatterer.

III MAGNETIC TRAPPING OF LIGHT

Bidispersed magnetic colloid is composed of micrometer-sized magnetizable spheres and nanomagnetic particles. Light Transport in such scattering media or in partially ordered systems shows several novel and useful phenomena. The most intriguing phenomenon is that of the storage and retrieval of light. [40-42] Attempts were made to transport the stored light for some distance. [43] In this experiment, scatterers were nonmagnetic particles surrounded by a nonmagnetic medium. When scatterers are magnetic spheres and the surrounding medium is magnetically active, they exhibit novel photonic effects. [44-47] Patel et al. demonstrate a scattering system that can transport the stored light some distance. The most fascinating effect is the trapping and release of light with the help of an externally applied magnetic field. [48] Further, In other experiment, linearly polarized light was allowed to pass through a diluted sample of bidispersed colloid. The light is transported through the colloid and magnetic field applied in perpendicularly to the light. The light emerges out from the sample disappears at some definite value of magnetic field which is known as critical magnetic field. The light reappears when the field is slightly more or less than critical field. The system was then subjected to the critical field and was exposed to the incident light for some time and then the light shutter was closed. Under this condition, the field was switched off. Almost immediately, a flash of light with the same frequency and state of polarization as that of the incident light was observed. This indicates the trapping of light at the critical field and its release when the field was removed. [49] The refractive index mismatch between micrometer-sized magnetic spheres and the surrounding magnetic colloid is responsible for the trapping of light. In the bidispersed colloid the magnetic micro spheres act as a Mie scatterer while the nano particles of surrounding fluid act as Rayleigh scatterer. Tuning is sustained as long as the field is present and the light remains trapped within the magnetic spheres. The technique of on-off of the light is simple, inexpensive, and operates at room temperature. Further, the fluctuations in time delay in emission of resonantly trapped light in microspheres of magnetite obey Levy distribution. [50] Since synthesis of the bidisperesd magnetic colloid is easy and the technique to tune Mie resonance is simple it will be useful to develop novel photonic devices.

IV MAGNETIC COLLOID WITH NEGATIVE REFRACTION

The materials with negative value of refractive index are know is Left Handed Materials (LHM). The concept of negative refraction was introduced by taking negative values of dielectric constant (ε) and magnetic permeability (μ). [51] The fabrication of such material was also demonstrated later on. [52-53] Classically, the refractive index is given by $\eta = \sqrt{\varepsilon\mu}$. For the refraction by traditional materials, both ε and μ are positive. But, in case of LHMs both ε and μ are negative. Such materials show some fascinating optical phenomena. The electrodynamics of LHMs is entirely different from electrodynamics of traditional material. The electrodynamics of negative refraction can be explained through Drude-Lorentz model. In this model, the atoms and molecules of a real material are replaced by a set of harmonically bound electron oscillators, resonate at some frequency ω0. For frequencies less than or more than ω0, an applied electric field displaces the electrons from the positive core, inducing a polarization in the same direction as the applied field. But, at frequencies near to ω0, the induced polarization becomes very large due to resonance; the large response represents accumulation of energy over many cycles, such that a considerable amount of energy is stored in the resonator. This stored energy is so large that can change the sign of the applied electric field. That is, as the frequency of the driving electric field is swept through the resonance, the polarization turns from in-phase to out-of-phase and the material exhibits a negative response. If the material response was due to harmonically bound magnetic moments, then a negative magnetic response would exist, which is less common in positive materials, therefore, negative materials are nevertheless easy to find. Some materials with negative ε include metals (e.g., gold) at optical frequencies and materials with negative μ include resonant ferromagnetic or antiferromagnetic systems. The negative material occurs near resonance has two important aspects. (1) Negative material will exhibit frequency dispersion. (2) The usable bandwidth of negative materials will be relatively narrow compared with positive materials. For existing materials resonance frequencies are found of the order of THz. On the other hand, resonances in magnetic systems typically occur at much lower frequencies. This is why materials with both negative ε and μ are not readily found. The general expression for ε and μ are given by Pendry et al. [54].

$$\varepsilon = 1 - \frac{\omega_{ep}{}^2 - \omega_{e0}{}^2}{\omega^2 - \omega_{e0}{}^2 + i\gamma\omega_{e0}}$$

$$\mu = 1 - \frac{\omega_{mp}{}^2 - \omega_{m0}{}^2}{\omega^2 - \omega_{m0}{}^2 + i\gamma\omega_{m0}}$$

Here, ω_{ep} and ω_{mp} are electric and magnetic plasma frequencies, ω_{e0} and ω_{m0} are low frequency edges of the appropriate bands and γ is the damping factor.

Almost all the existing methods for achieving LHMs were proposed for the solid materials. Construction of LHMs with fluids has not been established so far. However, magnetic colloids can be used as strong LHM with desired physical properties; hence, nowadays optical refraction in such soft materials is an interesting area for many researchers. Optical negative refraction for magnetic colloidal system containing Fe_3O_4 nanoparticles coated by an Ag shell, in the presence of z-directed magnetic field was presented by Y Gao et al. [55]. In this work they have use effective medium approximation and a 2D finite element simulation.

V Prospective of Future research in Light Transport through Magnetic Colloid

A new approach to understand light transport in magnetic colloid can be developed. The temperature and size dependent anisotropy model will be developed for bidispersed magnetic colloidal syatem. Theoretical model can be developed for morphological Mie-scattering. In the magnetic carriage of light the trapping time varies randomly from 30 to 230 milliseconds. [50] This trapping time can be extended up to few seconds. Magnetic colloid based novel metamaterial can be constructed for negative refraction. One can engineer the spatial dielectric constant by the external magnetic fields for reconfigurable optical devices, such as lenses [56], invisible cloaks [57], and waveguides.

VI.CONCLUSION

Some fascinating properties of light transport in magnetic colloids are reviewed. This study gives better insight to the optical parameters like refractive index, trapping time etc. during the transportation of light in presence of magnetic field. The tuning of refractive index in light transport in magnetic colloid is discussed. The negative refraction for the magnetic colloid is discussed. The study helps to design novel magneto optical and photonic devices, in which the light transport can be controlled. This work suggests a new way for designing tunable, active metamaterials.

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