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TOPICAL LIGHT TRANSPORT STUDY FOR MAGNETIC COLLOIDS: A REVIEW

Hem Bhatt[1] , Keyur Khatsuriya[1]

Abstract- Transportation of light through magnetic colloids is emerging area of research in the in the field of science and engineering. In this paper, we report and review some fascinating optical properties of light transport for magnetic colloids such as magnetic tuning of refractive index, magnetic trapping of light and negative refraction. Possibility of further research in light transport studies are also presented at the end. We have also reviewed the optical properties for Bi-dispersed magnetic colloids in presence of external magnetic field. These studies aid advancement of novel photonic devices which in turn advances the optical communication system.

Keywords –Bidispersed fluid; Refractive index; Magnetic carriage; Mie scattering; Negative refraction

I. INTRODUCTION

Magnetic Colloid (MC) which is also known as Magnetic Fluid or Ferro-fluid 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 Colloids. 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 colloids [6, 7], nanoparticles are electrically charged to keep the colloidal system stable. In Bidispersed Magnetic Colloids (BMC) microsized spherical particles are dispersed in nano magnetic fluid. [8]

Light transport through MC 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 long columns at high particle concentration. When light is transported through MC in presence of external magnetic field, it shows 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, MC 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, MC is the best suitable nanoelectrochemical system, if one wants to engineer novel photonic devices with desirable optical properties. The range of applications and fascinating properties of MC motivated us to pursue this study.

II. RECENT TREND IN LIGHT TRANSPORT STUDY FOR MAGNETIC COLLOIDS

Research on the advancement of the photonic devices has been the area of interest for many researchers because of their wide application in the area of optical and wireless communications. Some novel phenomena in the light

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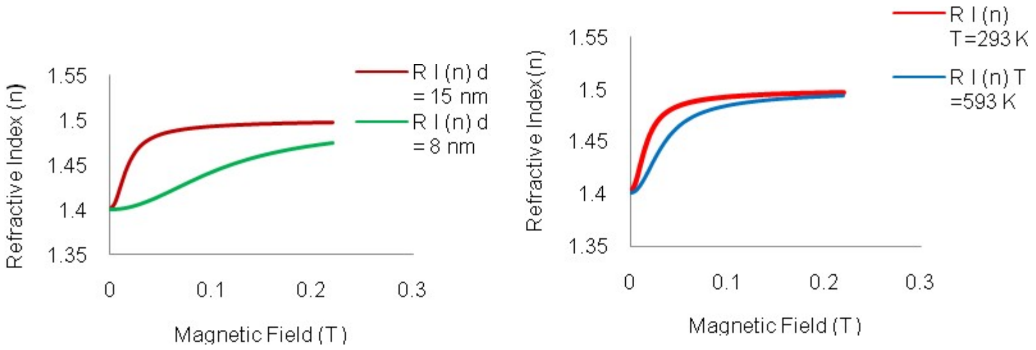
[1] *Shantilal Shah Engineering College, Sidsar, Bhavnagar*

transport such as tuning of refractive index, magnetic trapping of light, optical fiber communication with MC, negative refraction are some of the emerging areas of nanophotonics. Theories and mathematical modeling in the innovation of MC based ‘soft’ materials are yet to be in developing stage. Such studies lead us to the design and develop novel photonics devices.

III. MAGNETIC TUNING OF REFRACTIVE INDEX

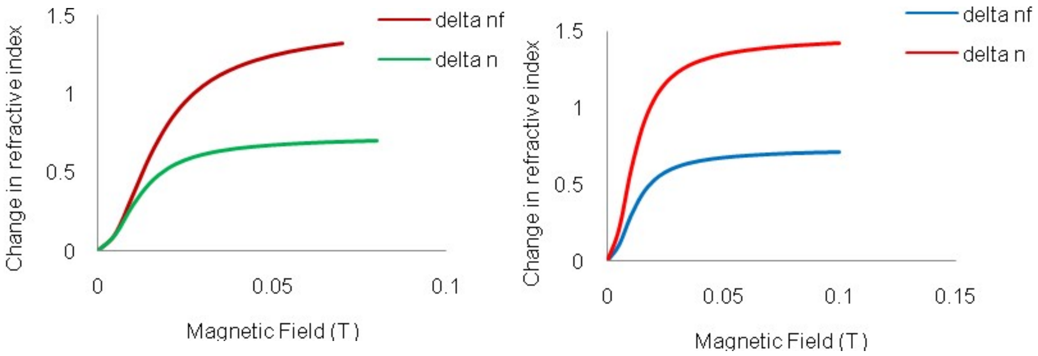
It was observed that the presence of external magnetic field tunes the refractive index of the MC. [32] It was reported that the refractive index (n) of MC increases with the external magnetic field and saturates. [33] For small particle size (< 10 nm) the transmitted intensity increases with external magnetic field but decreases for the particle size more than 10 nm. This is due to effects of van der Waals forces and magnetic dipole-dipole interaction. [34] In our recent work, the variation in refractive index with temperature and particle size was reported for MC. [35] For MC entire 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. Theoretical results show that refractive index tends to saturate (due to chains or columns formation) “early”, when the particle size is large and temperature is low. Fig. 1 shows the refractive index response to the magnetic field.

However, the chain formation is not possible for BMC in which micrometer sized particles are stably dispersed in magnetic nano fluid. Thevariation in refractive index due to field induced structure formation may not be possible when particle size is of the order of micrometer. The modulation in refractive index for such colloids 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. [36-37] Light transport through BMC is affected by refractive index of scatterer (n). The relative refractive index can be calculated by taking ratio of refractive index of scatterer (n) to the refractive index of nano-magnetic fluid (nf). We choose two different values of refractive index for scatterer as n = 2 and 4 and the change in refractive index were calculated. Plot of change in refractive index versus external magnetic field are shown in fig.2 (a) and (b).



(a) (b)

Figure 1. Refractive index (n) versus applied magnetic field (in tesla) for (a) two different diameters (8 nm and 15 nm) at constant temperature of 300 K and (b) different temperatures, i.e. 293 K and 593 K for particle diameter of 15 nm.



(a) (b)

Figure 2. Change in refractive index versus applied magnetic field (in tesla) for (a) ns = 2 (b) ns = 4

I.

The results show that the change in refractive index of MC (without microspheres) is less compared to BMC. Though, both are saturated at some magnetic field. The reason for such behavior is extinction of light in BMC. [38] In BMC the dispersed micro spheres will act as Mie scatterer and surrounding nano magnetic fluid acts as Rayleigh scatterer. Both scattering phenomena are different; it produces the refractive index mismatch. This mismatch produces the resultant oscillations in certain optical parameters called Mie resonance. [37] We found that the Mie resonance is responsible for the behavior shown in Fig.2.

IV.MAGNETIC TRAPPING OF LIGHT

As discussed earlier BMC is composed of micrometer-sized spheres and nano magnetic fluid. In BMC, if, micrometer sized particles are taken as magnetic microsphere then light transport in such scattering media or in partially ordered systems show several novel phenomena. The most intriguing phenomenon is the storage and retrieval of light. [39-41] Attempts were made to transport the stored light for some distance. [42] In such experiments, scatterers were non-magnetic particles surrounded by a non-magnetic medium. When scatterers are magnetic spheres and the surrounding medium is magnetically active, they exhibit novel photonic effects. [43-46] Patel et al. demonstrated a scattering system that can transport the stored light up to some distance. [47, 49] They observed that upon application of external magnetic field to BMC and simultaneously monochromatic, linearly polarized, coherent beam of light was passed, the light is trapped inside the colloid at a critical value of applied field. The photons remain trapped as long as the external magnetic field is on. When the field is switched off, photons are emitted from the BMC with the same wavelength as that of incident, but with lesser intensity. This indicates the trapping of light at the critical field and its release when the field was removed. Critical magnetic field depends upon the size of magnetic spheres and wavelength of incident light as shown in Fig.3.

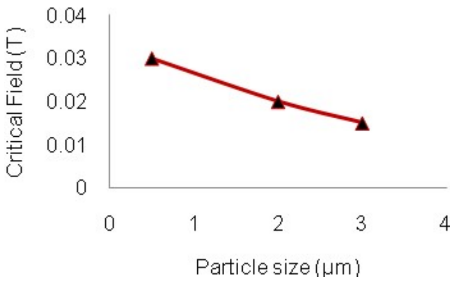


Figure 3. . Critical magnetic field (in tesla) versus particle size plot for wavelength 532 nm.

For 633 nm wavelength the critical field is found to be 0.016 T and 0.01 T for 2 μm and 3 μm size respectively. [49]

The refractive index mismatch between micrometer-sized magnetic spheres and the surrounding nano-magnetic colloid reduces the transmission intensity. In BMC, as discussed in earlier section, the magnetic micro spheres act as a Mie scatterer. Mie calculation shows that increase in particle size increases the forward scattering intensity which in turn shows the sharp resonance called Mie resonance. The oscillatory behavior in $\langle\cos\theta\rangle$ (anisotropy factor), kl^*(size parameter), vE (energy transport velocity) and D (diffusion constant) were reported by Bhatt et al. [36] It was envisaged that high resonance field gradient near the surface of Mie spheres may trap the light. [48] Tuning is sustained as long as the field is present and the light remains trapped within the magnetic spheres. Further, the fluctuations in time delay in emission of resonantly trapped light in microspheres of BMC follow Levy statistics. [50] Since the synthesis of the BMC is easy and the technique of on-off of the light is simple, inexpensive, and operates at room temperature, it will be useful to develop novel photonic devices. Also such phenomena will lead to some impending applications in the field of optical data storage and transmission.

V. Novel Magnetic Colloids with Negative Refraction

The materials with negative value of refraction are known as 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 $\eta =$. 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 diagram given below shows the phenomena of negative refraction.

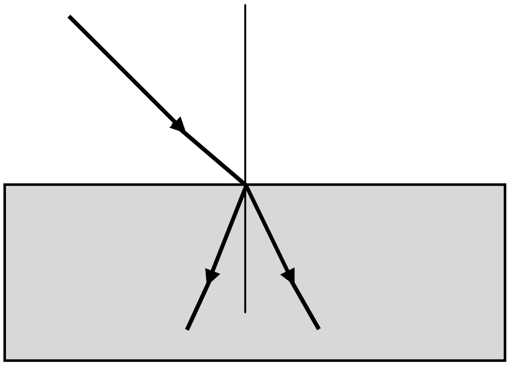


Figure.4. Schematic of positive and negative refraction

The electrodynamics of LHM 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 ω_0. For frequencies less than or more than ω_0, 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 ω_0, 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 not easy to find. Some materials with negative ε include noble 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, ωe0 and ωm0 are low frequency edges of the appropriate bands and γ is the damping factor.

Almost all the existing methods for achieving LHM were proposed for the solid materials. Construction of LHM with fluids has not been established so far. However, MCs may be strong candidate as LHM with desired physical properties; hence, nowadays optical refraction in such soft materials is an emerging area for research. A theoretical model of 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 their work they have used effective medium approximation and a 2D finite element simulation. Light transport properties of MC based LHM may be manipulated by designing novel magnetic colloid in which Ag shell is replaced by another material and by changing the operating frequency. We are at present working on the development of mathematical model for such LHM. There is scope of negative refraction for BMC due to magnetic control of light transport in it.

VI. PROSPECTIVE OF RESEARCH IN LIGHT TRANSPORT STUDY FOR MAGNETIC COLLOIDS

Light transport through MC is an emerging area for new research. In some recent work magnetically controlled light transport for optical fiber has been reported. [56-58] Novel photonic devices were proposed by Y. Zhao at al. [59] A new approach to understand light transport in MC can be developed. Theoretical model of temperature and size dependent anisotropy may be developed for BMC. In section 4 the observations show that the light trapping time varies randomly from 30 to 230 milliseconds. [50] A new technique shall be developed to extend trapping time up to few seconds. MC based novel LHM can be constructed for negative refraction. With the help of MC based LHM one can engineer the spatial dielectric constant by the external magnetic fields for reconfigurable optical devices, such as lenses [60], invisible cloaks [61], and waveguides.

VII. CONCLUSION

Some fascinating properties of light transport in magnetic colloids are reviewed and discussed. This study gives better insight to the optical parameters such as refractive index, trapping time etc… during the transportation of light in presence of external magnetic field. The magnetic tuning of refractive index in light transport in MC and BMC, magnetic trapping of light and MC based LHM are discussed in detail. The prospective of research in all light transport area is also presented. The study helps to design novel magneto optical and photonic devices, in which the light transport can be controlled by external magnetic field. This work suggests a new approach for designing tunable, active metamaterials.

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