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Polarized light transmission in ferrofluids loaded with carbon nanotubes in the presence of a uniform magnetic field

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ABSTRACT

Magneto-optic phenomena in ferrofluids have been shown to be related to the formation of chain structures, due to the arrangement of the ferromagnetic particles, induced by an applied magnetic field. In this work, the effects on transmission of polarized light due to anisotropic effects induced by an external magnetic field in ferrofluids with carbon nanotubes are studied. The time response of the system presents two well defined stages, in the first one, which is very short, the fluid behaves as a polarizer. In contrast in the second stage, the effects of light transmission dominate. In this stage the transmitted light intensity grows with time and after a long time reaches a constant stable value. It is shown that these phenomena depend on the carbon nanotubes concentration as well as on the strength of the applied magnetic field. Using a simple model that considers a chain-like structure formation, it is possible to determine the rate of agglomeration of the formed structures and the attenuation coefficient of the transmitted light. The formation of nanostructures leads to variation in the transmitted light, depending on the polarization of the incident light. These magnetic nanostructures can find numerous applications in nanotechnology, optical devices and medicine.

1. Introduction

A ferrofluid is a stable colloidal suspension of small ferromagnetic particles, with typical dimensions of the order of 10 nm, suspended in a liquid carrier [1]. The physical properties of these magnetic fluids can be modified in the presence of an external magnetic field.

Ferrofluid nanoparticles are superparamagnetic, having the property of being susceptible to become aligned in the direction of an external magnetic field. When this magnetic field is removed, the particles lose their magnetization and return to a random orientation, in a time scale which depends on the physical properties of the fluid and those of the nanoparticles. In the absence of an external magnetic field, the ferrofluid is isotropic. However, when a ferrofluid is exposed to an external magnetic field, it develops optical anisotropy due to the formation of microstructures such as field-induced chains [2].

In recent years, the study of the optical properties of ferrofluids has been of great interest, due to the wide variety of possible applications based on the magneto-optical phenomena. Such is the case of birefringence, dichroism, light scattering, ellipticity and Faraday rotation [3–6]. The behavior of these materials is the basis of the functioning of a variety of optical devices [7].

Optical characterization of these systems has shown that the structure of these systems has a strong dependence on the presence of a magnetic field, and that such behavior evolves in time [8]. For this reason, optical transmission studies of ferrofluid in an applied magnetic field have attracted the attention of diverse research groups [9,10]. The intensity of the light, transmitted through a suspension of nanoparticles of magnetite (Fe_3O_4), shows variations due to the dependence of the optical transmission coefficient with the formation of chains in the suspension. Based on experimental observations of samples with very low concentration of particles [11], it has been claimed, from the theoretical point of view, that the time evolution of the agglomeration in structured systems induced by an external field, occurs in two steps, starting with the assembling of chains followed by formation of columns [12]. One of the simplest approaches corresponds to the model of chains, which states that under the action of an applied magnetic field, the particles are magnetized and aligned in the direction and intensity of the applied field [13]. In this approach, it is also shown that the formation of these structures depends on the time interval in which the field is applied [14]. From the microscopic point of view, the particles are placed one after another to form thin linear chains, distributed throughout the sample and oriented in the direction of the applied magnetic field

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[15]. Subsequently the interaction between the chains can form columns, that finally join to form stable structures that minimize magnetostatic energy [16].

Variations in the transmitted light, when a magnetic field is applied, is an indicator of the structures formed in the fluid [17,18]. Additionally the time dependence of the intensity of light transmitted through the fluid could provide information about its structural stability.

The description of phenomena related to the formation of internal structures and their influence on the macroscopic properties is one of the most exciting problems of physics of colloidal systems. Experiments have shown that the presence of carbon nanotubes (CNT) in ferrofluids affects favorably the response of the compound to a magnetic field [19]. Filling or coating the CNT with magnetic nanoparticles has shown that superparamagnetic nanostructures in the form of columns or chains can be created [20–22]. These results suggest that adding CNT to ferrofluids might be a way to improve the anisotropic effects in the structure of the compound when a magnetic field is applied. However, the development and stabilization of these structures in the compound is not yet fully understood, even for low-intensity magnetic fields [23].

In order to induce magnetic order in CNT, it has been suggested that the nanotubes can be coated or filled with magnetic particles [24–26]. The surface encapsulation process would be possible through non-covalent bonds between the particles and tubes. But in the absence of a chemical reaction or electrostatic bond in defects on the surface, this process can be due to the minimization of van der Waals potential between the nanoparticles and the cylindrical nanotubes [27,28]. Samohous et al. [29] proposed a simple technique to obtain ferrofluid-coated CNT, which consists in preparing a composite of these materials at certain concentrations and subjecting the mixture to sonication. They found that the CNT coating is favored in ferrofluids with low hydrophobicity, as is the case of kerosene-based ferrofluids.

It is expected that CNT inside ferrofluids can enhance the formation of column-like structures which can be aligned in the direction of the magnetic field [30]. It has been shown that the formed chains could attract each other forming larger structures and achieving stability. Physical properties of the CNT-ferrofluid can change appreciably during the stabilization process. Optical properties should be among the most sensitive parameters that would change during this process. Additionally the magnetically induced effects on the CNT-ferrofluids can be a useful tool in understanding the arrangement of the chains as well as the time and spatial scales in which the phenomena are occurring.

2. Experiments

Ferrofluid samples were prepared at 0.1% volume concentration fraction using ferrofluid (Ferrotec EMG900) iron particles with size of 10 nm and isoparaffin (Ferrotec EMG900) as solvent. CNT are 50–80 nm in diameter and have lengths of 0.5–2 μm (Nanostructured and Amorphus Materials, 95%). Using these ferrofluids, CNT-ferrofluids samples were prepared at different volume concentrations fraction of CNT of 0.05%, 0.1%, 0.15%. Then the samples of ferrofluid with CNT were subjected to ultrasonication (Sonics Vibracell VCX130PB) for 1 min.

The sample was introduced into a specially designed cylindrical cell (7 mm of diameter and 5 mm of height) closed on both sides by transparent windows. By moving one of the walls, the height of the cell was varied using a micrometer coupled with a stepper motor. The cell with the sample is placed between a pair of Helmholtz coils. The sample is illuminated through one of the glass windows with polarized blue light of a Light Emitting Diode (LED) at 460 nm controlled by a diode laser driver (Melles Griot 06DLD205) in order to avoid fluctuations in the optical power.

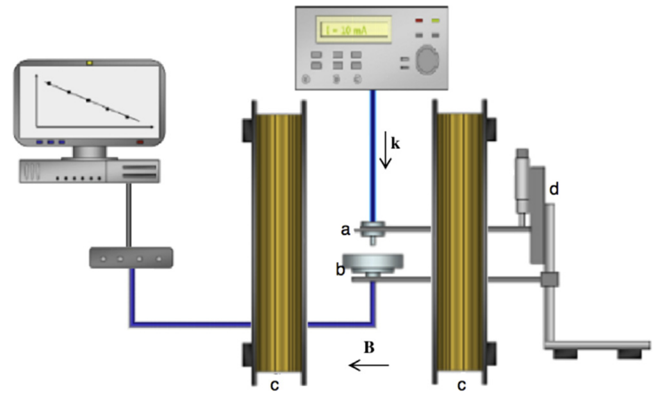

Fig. 1. Experimental setup used for the study of the time evolution of the transmitted light through ferrofluids loaded with CNT. (a) Blue LED, (b) cell with the sample, (c) helmholtz coils, and (d) micrometer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

The measurements were made for two directions of polarized light, which were perpendicular and parallel to the direction of the magnetic field. The transmitted light was collected by an optical fiber and measured with a spectrophotometer (Ocean Optics S2000) (See Fig. 1).

The sample cell thickness was increased in order to be able to perform light transmission measurements in samples with very high light absorption such as our CNT-ferrofluids samples. The thickness was changed up to reaching a region in which the validity of the Beer–Lambert law can be guaranteed. This procedure would permit to compare, in similar conditions, samples with very different concentrations of carbon nanotubes. The thicknesses of the ferrofluid samples without CNT and load of 0.05% of CNT were of 300 μm, and 200 μm for samples with 0.1% and 0.15% of CNT. With these values of thicknesses it is possible to get a good light transmission across the used samples. In these cases, the intensity of the transmitted light through each type of sample exhibits an exponential decay regime when the thickness is increased.

Starting with a very small thickness of the cavity, the intensity of the transmitted light was recorded. Slowly, and in steps of 10 μm, the height of the cavity is increased and the transmitted light is monitored. The interval of thickness in which the transmittance shows an exponential decay is also particularly interesting because it could provide the effective optical absorption coefficient. After that, the current in the coils were turned on, to generate a magnetic field perpendicular to the direction of the incident light ($\vec{k}$), and the transmitted light was monitored as a function of time. Magnetic fields of 85, 170 and 255 Gauss were applied. For all configurations, the transmitted light was monitored for each sample with the magnetic field turned off and then with the magnetic field turned on. The intensity of the transmitted light ($T(\vec{B})$) was normalized with the intensity of the transmitted light measured before applying the magnetic field ($T(\vec{B}=0)$).

3. Results and discussion

Samples with 0.1% volumetric concentration of ferrofluid (φ_{FF}) and with concentrations of 0%, 0.05%, 0.10% and 0.15% of CNT (φ_{CNT}) were studied. Due to the relationship between concentration and intensity of light transmitted by a sample thickness was determined according to Lambert Beer's law. The thickness of the ferrofluid samples without CNT and load of 0.05% of CNT was of 300 μm, and 200 μm for samples with 0.1% y 0.15% of CNT. With