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Journal of Magnetism and Magnetic Materials



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Versatile ferrofluids based on polyethylene glycol coated iron oxide nanoparticles

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ARTICLE INFO

Article history: Received 17 August 2011 Received in revised form 20 December 2011 Available online 3 February 2012

Keywords: Ferrofluid Polyethylene glycol Magneto-optics Magnetite Rheology

ABSTRACT

Versatile ferrofluids based on polyethylene glycol coated iron oxide nanoparticles were obtained by a facile protocol and thoroughly characterized. Superparamagnetic iron oxide nanoparticles synthesized using a modified forced hydrolysis method were functionalized with polyethylene glycol silane (PEG silane), precipitated and dried. These functionalized particles are dispersable in a range of solvents and concentrations depending on the desired properties. Examples of tunable properties are magnetic behavior, optical and magneto-optical response, thermal features and rheological behavior. As such, PEG silane functionalized particles represent a platform for the development of new materials that have broad applicability in e.g. biomedical, industrial or photonic environments. Magnetic, optical, magneto-optical, thermal and rheological properties of several ferrofluids based on PEG coated particles with different concentrations of particles dispersed in low molecular mass polyethylene glycol were investigated, establishing the applicability of such materials.

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1. Introduction

Ferrofluids are stable colloidal dispersions of very fine superparamagnetic particles with a size in the lower nanometer range [1–3]. The design and production of ferrofluids is currently under intensive investigation due to the broad applicability of such materials. Specifically designed ferrofluids are used in the biomedical branches as e.g. magnetic resonance contrast agents [4], magnetic drug targeting [5] or cancer hyperthermia treatment [6], for sensors for e.g. temperature [7] or magnetic fields [8] or for other applications like dynamic seals [3] or magnetically deformable mirrors [9]. As each of these applications requires adapted fluid properties, it is important to develop versatile synthetic methods for ferrofluid production. Several protocols have been published to stabilize the superparamagnetic particles in dispersion in order to prevent aggregation by Van der Waals forces or magnetostatic interactions, enabling ferrofluid production. Possibilities are coating particles with surfactants as e.g. oleic acid with kerosene as carrier fluid [10], preparing ionic ferrofluids by using e.g. tetramethylammonium [11] or using covalent chemistry to link the stabilizer and the particle [2]. The choice is mainly influenced by the envisioned application of the synthesized fluid. As stability is very important in biomedical applications, for

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example, a covalent bond connecting the stabilizer with the particle is appropriate. In this work, silane chemistry was exploited to provide a stable covalent bond between the stabilizer and the iron oxide nanoparticle surface. The stabilizer used, polyethylene glycol (PEG), is a very interesting polymer because it is soluble in both polar and some non-polar solvents, is quite inert to chemical treatments and biocompatible [12]. An impression of an iron oxide nanoparticle coated with a PEG silane is shown in Fig. 1. When dispersed in a solvent, PEG chains provide strong steric repulsion, enhancing stability of PEG coated particles [2]. As such, PEG coated particles can be dispersed in a range of solvents as e.g. water or polyethylene glycol to form stable ferrofluids. The magnetic, thermal, rheological, optical, and magneto-optical properties of ferrofluids composed of PEG silane coated iron oxide nanoparticles dispersed in different concentrations in low molecular polyethylene glycol were investigated. Using this knowledge, new applications based on ferrofluids composed of PEG coated superparamagnetic iron oxide nanoparticles can be developed.

2. Materials and methods

2.1. Synthesis of iron oxide nanoparticles

Iron oxide nanoparticles were synthesized using an in-house modified force hydrolysis method [13]. Briefly stated, analytical grade ferric chloride (FeCl₃) was used as salt precursor, ethylene glycol as solvent and reductant and *n*-octylamine as capping

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^{0304-8853/\$ -} see front matter \circledcirc 2012 Elsevier B.V. All rights reserved. doi:10.1016/j.jmmm.2012.01.032



Fig. 1. An iron oxide nanoparticle of which the surface was modified with PEG silane.

agent and preliminary coating layer. Typically, 37.5 ml ethylene glycol and 25 ml *n*-octylamine were poured into a flask and heated to 150 °C. In a beaker, 2.4 g FeCl₃ was dissolved in 10 ml ethylene glycol and 3.5 ml of purified water. After dissolving the salt, the ferric iron solution was added dropwise to the flask and further heated to reflux at 180 °C for 24 h. When the synthesis had ended, particles were precipitated from the reaction mixture using a magnet and washed with acetone. After washing the particles three times, they were dried in vacuo to obtain a powder of iron oxide nanoparticles with a typical yield of 1 g.

2.2. Silanization and ferrofluid synthesis

The silanization protocol started with dispersing previously synthesized *n*-octylamine coated nanoparticles in toluene by sonicating for +2 h to ensure maximal dispersion of the particles in the solvent. Typically the amount used was 100 mg nanoparticles per 100 ml solvent. Then 1 ml of methoxy(polyethyleneoxy)propyltrimethoxy silane (PEG Silane, ABCR chemicals) per 100 mg nanoparticles was added, together with trace amounts of acetic acid (CH₃COOH). The latter acted as a catalyst for the hydrolysis and condensation of silane groups on the particles surface and thus for the exchange reaction as a whole. The mixture was then again sonicated for +2h to ensure an optimal reaction medium. After sonication, the majority of the used toluene was evaporated using a rotavapor. The dispersion was then put on a magnet and heptane was added to promote the precipitation of coated particles. Precipitated particles were washed three times with acetone and dried in vacuo. These dry PEG coated particles could then be redispersed in a desired solvent and concentration for formation of a ferrofluid. For this, a known amount of coated particles was added to an amount of solvent (e.g. PEG 400 or water) and sonicated for $\pm 2 h$ to gain an isotropic ferrofluid.

2.3. Experiments

Transmission Electron Microscopy (TEM) experiments were done on a JEOL JEM2100 apparatus using an acceleration voltage of either 80 kV or 200 kV. Room temperature X-Ray Diffraction (XRD) patterns of powders were collected with a horizontal Geigerflex diffractometer in the reflection mode (Bragg-Brentano geometry), mounted on a Rigaku RU-200B rotating Cu-anode ($\lambda = 1.54$ Å) at a power of 4 kW. The widths of the divergence, receiving and scattering slits were 2°, 0.15 mm and 0.5°, respectively. The diffracted X-ray photons were collected after Nifiltering on a scintillation counter. Powders were presented on a grease-coated glass plate. Data were taken pointwise for 20 s in steps of 0.02° between 3 and 95° 2 θ (with θ being half the diffraction angle). A silicon standard was measured under similar conditions to ensure a proper diffraction angle calibration and to allow for a correction of the peak widths due to instrumental broadening. A polynomial background was subtracted. Magnetization data were obtained from vibrating sample magnetometry (VSM) experiments performed on a VSM Maglab setup from Oxford Instruments at 300 K. To obtain infrared spectra, samples were measured on a Bruker Alpha FT-IR Spectrometer with a spectral range from 4000 cm^{-1} until 375 cm⁻¹. Dynamic light scattering (DLS) measurements were performed on an ALV CGS-3 (Langen, Germany) compact goniometer system equipped with a multi-tau digital correlator (ALV/LSE-5003). The light source was a 10 mW 632.8 nm He-Ne laser. Temperature was controlled by a circulating fluid bath with an accuracy of ± 0.1 °C. Samples were equilibrated at the set temperature for 30 min prior to any measurements. The experiments were carried out at scattering angles from 30° to 150° or 6.83×10^3 nm⁻¹ < q < 2.55 × 10² nm⁻¹, where *q* is the scattering vector given by $q = 4n\pi \sin(\theta/2)/\lambda$, with *n* the refractive index of the solution and θ the scattering angle. Thermal properties were investigated using a Mettler-Toledo 822 DSC instrument using open pans. UV/Vis/NIR spectra were recorded on a Perkin Elmer Lambda 900 spectrophotometer. Rheological experiments were performed using an MCR 501 stress controlled rheometer (Paar Physica, Austria). Rough and smooth geometries with a diameter of 25 mm and 50 mm with cone angles of 0.07 and 0.04 rad were used. Measurements using rough and smooth plates with different diameter and cone angles gave same results, confirming the absence of slip. The temperature was maintained at 22 °C using a Peltier element. Magneto-optical Faraday rotation measurements were done on two experimental setups. The first setup consisted of an 830 nm diode laser combined with an AC electromagnet (857 Hz), a Wollaston prism and two photodiodes. The details of this setup were published elsewhere [14,15]. Spectral Faraday rotation measurements were done on a second setup using a Xenon arc lamp combined with a photo-elastic modulator, a 1 T DC magnet and a photomultiplier tube. This last setup was simultaneously used to record spectral Faraday ellipticity data. UV/Vis/NIR, Faraday rotation and Faraday ellipticity measurements were done using 9 µm thick liquid films of the ferrofluid under study. Liquid thin films were produced by letting the fluid diffuse into a standard liquid crystal glass.

3. Discussion and results

3.1. Characterization of the iron oxide core

Polyethylene glycol coated iron oxide nanoparticles were characterized by TEM measurements as shown in Fig. 2. The obtained size histogram was fitted to a lognormal model. TEM results showed that the particles were highly crystalline and had an average core diameter of 7.63 ± 2.09 nm. The most relevant part of the background corrected XRD pattern is shown in Supplementary Information (see Supplementary Information S1). Observed spectrum is due to magnetite, Fe₃O₄ [16]. The dimension of the crystallites, D_{hkb} was estimated to be equal to 7.0 ± 0.5 nm based on the full width at half maximum, β , of the [400] reflection and using Scherrers equation

$$D_{hkl} = \frac{\lambda}{\beta \cos \theta} \tag{1}$$

Both the TEM and XRD size estimates are well below the size limit for superparamagnetic behavior, which is about 20–25 nm for magnetite [17,18].

Magnetization versus applied field loops at 300 K of dry PEG coated particles were measured using VSM. Negligible coercivity



Fig. 2. Transmission electron microscopy image of PEG coated magnetite nanoparticles dispersed in water. Inset: histogram of the counted particle diameters.

and magnetic remanence were observed (see Supplementary Information S2), indicating superparamagnetic behavior [1].

Magnetization loops of weakly interacting superparamagnetic systems can be described by a Langevin function. The length of the PEG-silane used as coating molecule was calculated using an MM2 Force field energy minimization. Results show a staggered conformation with a length of approximately 4.6 nm. As the polymeric PEG chains exhibit high degrees of steric hindering, particles even in dry powder will not be in contact with each other. This diminishes the interaction effects that constitute deviations from Langevin behavior. Thus, assuming non-interacting particles and uniform size, an estimate of the magnetic diameter can be obtained by fitting the data with a simple Langevin function. Using the density of magnetite (5.15 g/cm^3) and the experimentally measured saturation magnetization of 58 emu/g, a magnetic core diameter of 7.95 nm was calculated. Notice that this last value overestimates the structural size but is in good agreement with the values obtained from TEM and XRD measurements.

3.2. Characterization of coated particles

After coating the synthesized particles with PEG silane, the dried coated particles could be dispersed in hydrophilic solvents, affirming the effectiveness of the silanization procedure. In order to further verify the success of the silanization procedure, FTIR experiments were conducted on dry powders of *n*-octylamine coated particles and PEG coated particles. The particles were diluted in a 1/100 ratio in solid potassium bromide (KBr) and measured in transmission. The results of the measurements (see Supplementary Information S3) showed the disappearance of amine peaks and the onset of PEG silane specific bands, confirming the exchange of *n*-octylamine at the surface for PEG silane and indicating a successful silanization.

Dynamic light scattering experiments (DLS) were performed on PEG coated particles dispersed in PEG 400 to assess the hydrodynamic properties of the coated nanoparticles. A hydrodynamic diameter of 48.50 ± 2 nm was calculated from the results (see Supplementary Information S4). Note that the size distribution obtained from DLS measurements corresponds to a higher average than the one obtained from XRD or TEM measurements due to the intrinsic sensitivity of the technique to small aggregates present in the dispersion.

3.3. Characterization of ferrofluids

Ferrofluids were prepared by dispersing a known mass of dry PEG coated particles in PEG 400 as described above. The exact concentrations used in this work are shown in Table 1. Volume percentages were calculated from the mass percentages of particles using the densities of magnetite and PEG silane, the core size observed in TEM measurements and the thickness of the coating layer as calculated (4.6 nm), assuming a fully covered surface.

3.3.1. Magnetic properties

Magnetization vs. applied field hysteresis loops were measured using VSM to assess the magnetic properties of the synthesized ferrofluids (see Supplementary Information S5). As expected for ferrofluids, no coercivity or remanent magnetization was observed. The saturation magnetizations (M_S) as a function of the mass percentage of particles in the ferrofluids are depicted in Fig. 3. A linear increasing trend of the M_S as a function of the mass percentage of particles was observed.

3.3.2. Thermal properties

For many applications, thermal stability of the used ferrofluid over a large temperature range is very important. To assess the thermal properties of the synthesized fluids, differential scanning calorimetry (DSC) experiments were conducted on the 1, 5, 10 and 15 m% fluids (see Supplementary Information S6). Samples in an open pan were first cooled to -60 °C, then heated until 220 °C and this cycle was repeated three times. A very small fraction of water that was present in the fluids due to the hygroscopic behavior of polyethylene glycol was evaporated during the first heating step of the DSC experiment. No decomposition of the fluids until 220 °C was apparent from the DSC data, showing that the fluids can withstand such high temperatures. Features such as the melting temperature and the crystallization temperature varied little between the cycles for the same sample, demonstrating the excellent thermal stability of the synthesized ferrofluids. The crystallization and melting temperatures of all assessed fluids were in the same range. For example, the crystallization and melting temperatures for the 15 m% ferrofluid were approximately -15 °C and 5.4 °C. This means that the useful temperature range runs at least from 5.4 °C to 220 °C. It is important to note that, at least with low mass percentages of particles, the thermal properties depend mostly on the dispersion medium. By using PEG silane and PEG 400, which are high boiling and thermally stable substances, for the synthesis of ferrofluids in this work, excellent thermal and long term stability were acquired. In this

Table 1

Overview of samples used. The three columns are the names of the samples used in this work, the mass percentage (m%) and the volume percentage (V%) of particles in PEG 400.

Name (%)	m%	V%
0	0	0
1	1.01	0.78
2.5	2.51	1.94
5	5.03	3.89
7.5	7.54	5.83
10	10.07	7.79
15	15.07	11.66



Fig. 3. Saturation magnetization a.f.o mass percent particles in the ferrofluid as measured by VSM experiments. A linear increase of saturation magnetization with increasing mass percentages of particles was observed.



Fig. 4. Viscosity of ferrofluid suspensions as a function of shear rate for varying particle concentrations. The broken lines are fit to Sisko equation.

way, thermal properties of ferrofluids can be tuned by selecting a suitable dispersion medium.

3.3.3. Rheological properties

The viscosity of ferrofluid suspensions as a function for shear rate for varying particle concentration is shown in Fig. 4. The viscosity data in Fig. 4 are fitted to Sisko equation $\eta = \eta_{\infty} +$ $(K^n\dot{\gamma}^{n-1})$, where η is the viscosity, η_{∞} is the high shear limiting viscosity, $\dot{\gamma}$ is the shear rate, *K* and *n* are the fitting parameters [19]. For n=0 we get a Bingham model ($\sigma = K + \eta_{\infty}\dot{\gamma}$), where σ is the shear stress and for n=1 we get the Newtonian equation $(\eta = \eta_{\infty} + K)$. The parameters *K* and *n* for different concentration of particles are listed in Table T1 in the Supplementary Information. The increase in *K* and decrease in *n* with the increase in particle concentration indicates a change from Newtonian liquid to a Bingham plastic. This indicates that at higher volume fractions there is a weak interaction between the particles, which causes this upturn in the viscosity at low shear rates. As the shear rate is increased, the viscosity of the suspension for all volume fractions reaches the high shear limiting viscosity.

In Fig. 5, the relative high shear limiting viscosity data is plotted as a function of volume fraction. The line in Fig. 5 is the

prediction from Einstein equation $(\eta_{\infty}/\eta_s = 1+2.5\phi)$ for dilute suspension of hard spheres, where ϕ is the effective volume fraction [20]. The viscosity data follows Einstein equation because at high shear rate any structure that is present in suspension is broken down.

3.3.4. Optical properties

For optical and magneto-optical experiments and applications, it is very important that the absorbance of liquid thin films in relevant regions of the spectrum is sufficiently low. Transparency is essential to prevent a large loss of signal while transmitting light through the sample. The prepared thin films were of superior optical quality, being optically isotropic without any visible aggregation present. The UV/Vis/NIR spectra recorded for 9 μ m liquid thin films of the ferrofluids are shown in the Supplementary Information (Figure S7). Observed features in the spectrum are due to the presence of magnetite and Rayleigh scattering of particles in the fluids [21]. The absorbance at 800 nm, far from resonant features, increased linearly with increasing mass percentages of particles in the ferrofluids (see Supplementary Information S8).

3.3.5. Magneto-optical properties

To assess the potential of the fluids as magneto-optical sensor elements, Faraday rotation (θ_F) and Faraday ellipticity (η_F) experiments were performed. Faraday rotation is the difference in refraction and Faraday ellipticity the difference in absorption for left- and right-circularly polarized light when a material is subjected to a magnetic field in the propagation direction of the light beam. For Faraday rotation, the angle of rotation θ_F is given by the equation

$$\theta_F = VBL$$
 (2)

where *B* stands for the component of the magnetic field in the propagation direction, *L* the path length of the light in the sample and *V* the Verdet constant. The latter is a material property and quantifies the Faraday rotation. The magnetic flux density, *B*, can be decomposed in the applied magnetic field *H* and the magnetization as a response of materials to this applied field *M*. As such, we can rewrite Eq. (2) as

$$\theta_F = V(H+M)L \tag{3}$$

The magnetization, *M*, is further caused by a diamagnetic term linear in magnetic field from the glass background, surrounding air and organic substances and a superparamagnetic term from



Fig. 5. Relative viscosity of ferrofluid suspensions as a function of effective volume fraction. The full is prediction from Einstein equation for suspensions.

the nanoparticles. As seen in Section 3.1, the magnetization response of the used nanoparticles as a function of applied magnetic field is best described by a Langevin function. Eqs. (2) and (3) are also valid for Faraday ellipticity data. Fitting the obtained experimental Faraday rotation and ellipticity data was done using the following equations:

$$\theta_F = A_\theta + B_\theta \left(\left(\frac{\cosh(CH)}{\sinh(CH)} \right) - \left(\frac{1}{CH} \right) \right) + D_\theta H$$
(4)

$$\eta_F = A_\eta + B_\eta \left(\left(\frac{\cosh(CH)}{\sinh(CH)} \right) - \left(\frac{1}{CH} \right) \right) + D_\eta H$$
(5)

where A represents an offset factor. B is directly proportional to Faraday rotation or ellipticity, C is a parameter within the Langevin function which determines the shape of the curve and D represents the linear diamagnetic response. Using these equations for fitting ensures a correct treatment of the background signal from diamagnetic substances. For this work, the only important parameters are B_{θ} and B_{η} , since these are directly proportional to Faraday rotation and ellipticity. To increase the accuracy of the fitting procedure, all measured wavelengths of both Faraday rotation and ellipticity were simultaneously fitted. When using small magnetic fields, as in the AC Faraday measurements, a linear fitting procedure with Eq. (2) is appropriate. This because the magnetization, and thus the Faraday rotation and ellipticity responses, of the nanoparticles in small fields are linear to the applied magnetic field [1]. Using two experimental setups, the AC and DC magnetic field Faraday rotation and the DC magnetic field Faraday ellipticity were measured.

Important to note is that if a ferrofluid is subjected to a magnetic field, the superparamagnetic nanoparticles tend to align due to magnetostatic interactions. These induced morphological changes have an effect on the transmission and polarization of light passing through the sample [22]. To avoid large influences of these phenomena on the measurements, data was only recorded after the system was stabilized at a certain magnetic field strength.

In Fig. 6, the normalized DC Faraday rotation responses of the 2.5, 5, 10 and 15 m% particles in PEG 400 ferrofluids as a function of wavelength are shown. By convention, the Verdet constant of glass was taken to be positive. The features present in the spectra, i.e. a valley around 460 nm, a cross-over around 550 nm and a positive tail at longer wavelengths, were also observed in magnetite–polymer composites [23,24], silica gels containing maghemite [25] and ferrofluids based on maghemite and cobalt ferrite,

[26] modeled by Maxwell-Garnett [24] and modified discrete dipole approximation [23] theory and explained in terms of electronic transitions [27]. It can be seen that while the 2.5 m% sample barely exposed such features, these were very clear for the 15 m% sample. As the errors on the measurements for the used setup were on the order of 5%, caution must be taken regarding quantitative statements. Qualitatively, it can be stated that increasing the mass percentage of particles in the fluids accentuated the features present in the spectra. The valley around 460 nm became deeper and Faraday rotation responses for longer wavelengths rose with increasing mass percentages of particles.

Nor a redshift of the valley peak feature around 460 nm, or of the cross-over wavelength with increasing mass percentage of particles, as observed by other groups [23,24], could be confirmed within the studied concentration range. According to Ref. [23], in which a modified discrete dipole approximation method was used to calculate the Verdet spectra as a function of interparticle spacing, the shifts of spectral features occur through optical coupling. According to the authors, this effect only occurs when the interparticle spacing is smaller than 8 nm. Using the sizes of our particles obtained with TEM and DLS and the densities for magnetite and PEG silane, estimates of the interparticle distances in our agglomeration free ferrofluids were calculated. In the most concentrated sample with 15 m% of particles, the interparticle distance was approximately 120 nm. This interparticle distance thus was too large to see an interparticle optical field coupling effect. Furthermore, coupling was highly likely to be counteracted by the strong repulsive forces exerted by the PEG chains, keeping the particles well apart.

Results for Faraday ellipticity measurements are shown in Fig. 7. Spectral features present were a valley centered around 420 nm, a very broad band with a maximum around 560 nm and two cross-over points around 460 nm and 730 nm. From Fig. 7 it can be seen that increasing the mass percent of superparamagnetic iron oxide nanoparticles in ferrofluids also increasingly accentuated the spectral features present in the Faraday ellipticity spectra.

As stated earlier, Faraday rotation is the difference in refraction and Faraday ellipticity the difference in absorption for leftand right-circularly polarized light when a material is subjected to a magnetic field in the propagation direction of the light beam. Faraday rotation and Faraday ellipticity are connected to the real and the imaginary part of the off-diagonal components of the dielectric material function [27,28]. According to the Kramers–Kronig relations,



Fig. 6. Normalized DC magnetic field Faraday rotation of ferrofluids as a function of wavelength. Increasing the mass percentage of particles accentuates the spectral features that are present.



Fig. 7. Normalized DC magnetic field Faraday ellipticity of ferrofluids as a function of wavelength. Increasing the mass percentage of particles accentuates the spectral features that are present.



Fig. 8. AC magnetic field Verdet constants at 830 nm as a function of mass percent particles in the fluids. Increasing the mass percentage linearly increases the Verdet constant at both wavelengths.

Table 2Summary of obtained results.

Name (%)	M s (emu/g)	Viscosity (Pa s)	Verdet 830 nm (° $T^{-1} m^{-1}$)
0	-	0.110	-
1	0.34	0.1133	$1.9 imes 10^4$
2.5	1.21	-	$6.2 imes 10^4$
5	2.86	0.1176	$1.2 imes 10^5$
7.5	4.09	-	1.6×10^{5}
10	5.10	0.1300	$2.6 imes 10^5$
15	7.62	0.1464	3.92×10^5

this means that Faraday rotation and ellipticity are coupled [29]. This is apparent when comparing Figs. 6 and 7. While the Faraday rotation has a minimum around 460 nm, Faraday ellipticity for crosses from positive to negative around that wavelength. Vice versa, the broad peak feature present in the Faraday ellipticity spectra around 560 nm correlates to a cross-over of the Verdet constant in the Faraday rotation spectra.

To accurately assess the Verdet constants of the synthesized ferrofluids, an AC magnetic field setup using a diode laser at 830 nm, a Wollaston prism and two photodiodes was used. This wavelength was chosen because DC Faraday rotation measurements show a large signal in that region, combined with a very low absorbance of the signal as observed in UV/VIS/NIR spectra.

Results are shown in Fig. 8. As was expected, the Verdet constant rose linearly with increasing mass percentage of iron oxide nanoparticles in the fluids. The achieved Verdet constants are very significant for hydrophilic magnetite ferrofluids with values up to 3.92×10^{5} ° T⁻¹ m⁻¹ for the ferrofluid sample with 15 m% of particles. Important to note is that this is not the largest attainable Verdet constant, since according to the data shown in Fig. 6, the Verdet constant will be the largest around 460 nm. Numerical results obtained on the ferrofluids synthesized in this work are summarized in Table 2.

4. Conclusion

In conclusion, a facile and versatile synthesis of broadly applicable ferrofluids was proposed. Ferrofluids based on PEG coated superparamagnetic iron oxide nanoparticles dispersed in PEG 400 were magnetically, thermally, rheologically, optically and magneto-optically characterized. It was observed that the saturation magnetization, the absorbance in the UV/VIS/NIR and the AC magnetic field Faraday rotation at 830 nm increased linearly with increasing mass percent of particles in the fluids. DSC experiments showed that the synthesized ferrofluids possess excellent thermal stability and a large useful temperature range. DC Faraday rotation and ellipticity experiments revealed spectral features of which depend on the mass percent of particles present. Furthermore, the coupling between Faraday rotation and ellipticity was clearly observed. Important to note is that besides the concentration of particles in a ferrofluid, also the used dispersion medium is a major determinant of the fluid properties.

By altering the mass percentage of PEG coated iron oxide nanoparticles in a ferrofluid, important properties could by tuned. Ferrofluids based on PEG coated iron oxide particles represent a versatile platform for the development of broadly applicable materials. Future work will include investigation of the properties of ferrofluids based on similar particles but dispersed in other media or coated by other organic molecules and expanding the wavelength range for magneto-optical measurements into the infrared.

Acknowledgments

The authors would like to thank G. Koeckelberghs, T. Nuytten, N. Brooks, S. Vandendriessche, M. Bloemen, M. Vanbel and P. Baatsen of the EM-facility of the Center for Human Genetics, VIB-KULeuven for useful discussions and help with experiments. We acknowledge financial support from the Fund for Scientific Research Flanders (FWO-V), the Agency for Innovation by Science and Technology in Flanders (IWT) and the Catholic University of Leuven (GOA). W.B. is grateful for support from the IWT. V.K.V. is grateful to the FWO-Vlaanderen.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jmmm.2012.01.032.

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