Physics of Functional Materials and Devices
Prof. Amreesh Chandra
Department of Physics
Indian Institute of Technology Kharagpur

Lecture – 32, Week 8
Ferrofluids

In this third lecture of week 8, let us continue our discussion on a different type of magnetic material and how they are becoming quite important for various applications. and these are Ferrofluids. Some of you may have heard about this term, but many of you may not have heard. So, I will give you the introduction to Ferrofluids. What are Ferrofluids? Are they difficult to fabricate or you can synthesize them easily? You will understand that the synthesis protocols for obtaining Ferrofluids are quite simple. You will see that the properties of these Ferrofluids can be tuned as you move from one type of Ferrofluids to the other and therefore, the applications of Ferrofluids are quite large and those would also be discussed and probably I will get time to discuss three or four of them more in detail.

What is a Ferrofluid? Ferrofluids are also called as Magneto-fluids. These are basically colloids which are typically consisting of 10 nanometer sized magnetic particles. These particles are the ones which are also coated with a surfactant in order to prevent aggregation. Now what is it doing? You have a particle and if you have large number of particles which are there in a fluid, what will happen? The probability of these particles to aggregate or agglomerate or coalesce meaning coming together is quite high.

So, what you may believe that you have very small size particles, but when you disperse them, you will find that after sometimes these particles they come together to form an aggregate. So, this is called agglomeration. So, you have a large size particle which constitute many smaller size particles within them. So, the advantages of nanoparticles are lost. So, you must ensure that nanoparticles are not aggregating when you want to derive the advantages of nanoparticles.

So, what do you do? You have a particle; you coat it with a surfactant. What is a surfactant? A surfactant is a material which has two ends, one is hydrophilic and the other is hydrophobic. That means, one likes water, the other is phobic to water. So, you have coating of this material with surfactants. Now if another particle which is coated with surfactant tries to come near it, you see you have these surfactant chain molecules which will repel each other and hence these two particles are kept separated from each other.

And that is a typical process by which the nanoparticles when they are being dispersed in a fluidic media to obtain a stable colloidal solution is made to stabilize in a way that they do not agglomerate. That is what is meant by coated with surfactant to prevent aggregation or agglomeration. Usually, these ferrofluids have liquids such as transformer oils or kerosene which act as the parent of this whole colloidal solution. That means these smaller size particles are dispersed in a transformer oil or a kerosene. These fluids may also be called as liquid magnets.

Typical examples of ferrofluids are nanoparticles of magnetite Fe_3O_4 dispersed in transformer oil or even kerosene. These are some of the images of ferrofluids. So, you can see that there is a well-defined arrangement of the particles of the magnetic nanoparticle. So, they are not agglomerating, they are ordering in a particular manner. If you want to see more applications of figures like this, the references from which these pictures have been taken is from the internet sources and you can obtain more detail from the references given below and due credit is being given to these references.

So, what do we see? These ferrofluids are soft magnets. Why? Please remember we have just mentioned that they can also be called as liquid magnets. So, they are soft magnetic materials that are superparamagnetic. In the previous lecture, I had talked to you about the MH loop of a superparamagnetic material. It does not have an open loop, but it shows that there is a saturation in the magnetization.

Ferrofluids have very interesting properties such as magnetic field dependent anisotropic optical properties. Anisotropic means what? It means if you take this material and for example, you take three axis x, y and z. You have an exciting wavelength falling on these fluids. Generally, you believe that the response characteristic should be same in all the three directions, same optical response in x direction, y direction and the z direction. But these ferrofluids have anisotropic properties.

That means the response characteristics in one of the directions can be very different to that in the other two directions. In 1960, the team led by Stephen Pappell at NASA first developed these ferrofluids. And what was the idea? It was basically the method of controlling the fluids in space. Now, each tiny particle of the ferrofluid is coated with a surfactant as we have seen earlier. They do not aggregate and if they do not aggregate means what? They are able to move easily and they are small So, their movement is uninhibited.

If you have a larger size particle, the motions are very different. Therefore, what you can do? You can have various magnets and different orders of magnetic field to control the nature of magnetic fluids. We have already seen in the Stoner–Wohlfarth model, that if you have elongated grain concepts, then you have one of these states which would be favored and then you can find out what is the magnetic properties at nanoscale. For example, the ferrofluids change their density in proportion to the strength of the magnetic field that is applied on it. So, it would change the density and the typical M-H curve is similar to what you get in a super paramagnetic material.

For example, if you look into these curves shown in the upper half of this slides, you can see that if you can take let us say Fe_3O_4 in fluids or you can take Fe_3O_4 powders, you can clearly see that the nature of loops which are opening or stabilizing are very different. So, you can tune the magnetic properties of let us say 6 nanometer size Fe_3O_4 particles just by dispersing them in a fluidic environment, where they are not coalescing and are forming homogeneous suspension or a colloid. When you apply a DC magnetic field, what happens? This causes the fluid to actually arrange itself in a solid mass with the given magnetic state, where the material is not a liquid. So, you are now actually stabilizing in a manner that you are having the features of a solid mass as you saw in the previous slide that was showing the pictures of ferrofluids. Now, how difficult are they to fabricate? Let us say if you want to make Fe_3O_4, what is the typical synthesis protocol? I have also discussed this during the week where I was talking about synthesis protocols.

So, you take solution of iron 2 or iron 3 sources in water path. Maintain the pH by adding sodium hydroxide or ammonia. Then if you increase the pH value, it would result in the formation of Fe_3O_4 very simple. And the corresponding reactions would be what? Fe^{2+} plus certain fraction of Fe^{3+} you have the OH ions giving you Fe_3O_4 plus water. The oxidation of magnets into this megamite occurs by natural weathering or processes that converts the Fe^{2+} to Fe^{3+} ions.

This creates the final product which would be a mixture of both magnets and magmites. And hence what you will get would be Fe_3O_4 plus certain protons giving you Fe_2O_3 plus water plus certain fraction of Fe^{2+} ions. This process results in the ferrofluid which primarily consists of a mixture of Fe_3O_4 and Fe_2O_3 and these are the two reactions which occur. So, you can stabilize these particles in a water based solution and then they get dispersed. Then you can homogenize the whole solution.

Once you have coated those particles with surfactants, you have stabilized the whole colloidal solution, what will you do with it? So, there are various applications of these ferrofluids. It ranges from medicines, spacecraft propulsion, electronic engineering, mechanical engineering, optics and material science. Let us start with a well known application of a ferrofluid and that is liquid crystal displays. The LCD TVs you may have heard which was being used before you had the LED TVs coming into the market. Now, it includes the application of ferrofluids and its response characteristics under an applied magnetic field, where this field induces the stabilization of wire fringes.

So, what happens? You have ferrofluids sealed in a glass cell having thickness of several micrometers. So, you have a glass cell in which you fill this ferrofluid. Please remember the concept remains the same that it is a stabilized solution with nanoparticles which are coated So, that they do not agglomerate. Now, you apply a DC magnetic field parallel to the surface and what is happen? The field is now examined by an optical microscope. Now, you have applied a field parallel to the surface.

What will happen? Some of the magnetic particles in the fluid would then try to align in the direction of the field and they would appear to getting agglomerated and forming needle like chain which are parallel to the direction of magnetic fields. So, small size particles applied magnetic field, these small particles behaving like elongated grains and because of the field these grains are now aligning in the direction of magnetic fields and if they are all particles pointing in the same directions then they appear like needle like chains, simple. As the field increases what would happen? More particles will join the chains and the chains will become broader as well as longer because it is not only one dimension, it is in two dimension and slightly you also have the third direction consideration which you will have to take into consideration. Second case when you apply the field in the perpendicular direction to the face of the film, the ends of the chains will arrange themselves in a pattern which is shown in the figure on the right-hand side. So, now these are arranging in particular order and now if you take a top view, you get these small size particles which are all arranging on the top surface.

If you have low fields what will happen? The ends of the chains would be randomly distributed in the plane of the fluid, but if you increase the fields magnitude there would be a critical field beyond which the chain ends would become ordered that is flipping of the type poles or the domains in this case. And what you will get is a two-dimensional hexagonal array as shown in the figure. So, from band fringes type arrangement you can go to the hexagonal array arrangement in 2D. So, in the field of optics we know the application of polarizers. Light is an electromagnetic wave; it has two components the E component and the B component and they are perpendicular to each other.

Now if you have a linearly polarized light where these vibrations are confined to one plane perpendicular direction of the propagation rather than having a random any transverse direction. So, it is confined in one of the directions. When this linearly polarized light is incident on a magnetofluid to which a DC magnetic field is applied what will happen? The light emerging from the other side of the film is elliptically polarized. Why? Because the applied field will interact with the magnetic field component of the EM wave and rotate the vector such that now you have an elliptically polarized light coming out of the other end of the sample. The elliptically polarized light occurs when it occurs when the E and the H vibrations around the direction of the propagation are confined in two mutually perpendicular planes.

This is what we know and these vibrations in each of the planes are out of phase. This effect is called the Cotton-Mouton effect. The figure which is shown in this slide shows the typical experimental arrangement for having a ferrofluid based polarizer. In this you can clearly see that there is a helium-neon laser which has linearly polarized light because of a polarizer in front of it. Now this polarized light is incident on the sample is incident on the sample which is based on magnetofluid film and to this you apply a DC magnetic field parallel to the plane of the film.

So, you apply a DC field. Now what you need to do? To examine the polarization of the light emerging out of the field what you need to do? You have to apply another polarizer which is now called as analyzer and place it between the detector and the sample and by rotating the analyzer you can find out what is the nature of light which is coming out of this sample after the application of magnetic field. If you plot the normalized intensity then of the light which is coming out through the analyzer you will find that the intensity of the transmitted light is a function of the orientation of the polarizing axis of the analyzer which is given by the angle eta and this is shown in the curve. And these effects are utilized for making optical switches where the intensity of the transmitted light is switched on or off using a DC magnetic field or by changing the orientation of the polarizer. Then comes a very interesting example that is the use of these magnetic fluids in tunable diffraction gratings. We know diffraction gratings is an optical component which has large number of slits in a small area.

So, suppose you have a grating which has a rating of 2500 LPI, that means, you have 2500 lines per square inch of the grating surface. Now comes a new term that is you are going to tune the nature of this diffraction grating by application of magnetic field. Diffraction is what? It is basically interference of two or more lights, the waves having the same wavelength, but the path which they travel may be slightly different and then they are made to come at the detector surface and interact with each other or the screen or the photographic film whatever you want to name it. When the path length differs by half wavelength or half a wavelength, the waves destructively interfere resulting in dark band, but if they are integer multiples then they interfere constructively. This is what we know and when there is constructive interference then you have bright band otherwise you will have dark bands.

Diffraction grating it consists small slits separated by distances of the order of wavelength of the incident light and I have already defined what is a diffraction grating. So, now when a DC field of sufficient strength is applied perpendicular to a magneto fluid what will happen? You saw in the first example an equilibrium two-dimensional hexagonal lattice is going to get stabilized with what? With columns of nanoparticles occupying the lattice sites. So, you will have ordered arrangements. If you take the top view what you will see? Hexagonal lattice structure. This structure can act as a 2D optical diffraction grating.

What it would do? It would diffract the incoming visible light. Now if you have diffraction grating concept then you have the multiplicity and if you have multiplicity concept coming into picture then you will have sharp bands which are separated from each other or sharp bands separated by dark bands. The film will experience this magnetic field that is applied and what will happen? If you see the diffraction condition you will have d sine theta is equal to n lambda, where d is the distance between the chains of nanoparticles, theta is the angle between the outgoing light and the direction of the light normal to the film and lambda is the wavelength. As the distance between the chain depends upon the strength of the DC field we can tune the diffraction grating. That is, it can be adjusted to a specific wavelength by changing the strength of the magnetic field.

So, if you change the field strength the ordering will change, the distance between the two columns will change and that means, the magnitude which will be corresponding to a given wavelength will change and hence you can tune the structure in a way that it diffracts different wavelength. And therefore, you can tune the diffraction grating and you can have a very easy method of having tunable diffraction grating. These are the other applications you can have vacuum seals; you can have seals for hard drives, you can have sealing of any other pieces where you need strong sealing between the components, you can have directional sensing or you can have audio speakers in the voice gap where you need some damping moving masses or you can use these magnetofluids in medical imaging techniques. So, to conclude you will see that we have talked about ferrofluids. These are very simple to stabilize, fabricate and use, but by changing different materials you can have different types of ferrofluids and as you have different types of ferrofluids you can have wide variety of applications for these ferrofluids which were also discussed today.

You can follow these books for developing more understanding about ferrofluids. This brings us to the end of today's lecture and I thank you for attending this lecture number 3 of week 8. Thank you very much.