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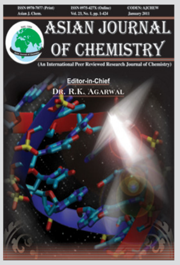

Left Handed Maxwellian Nature of Nano-Structured Layered Material-Mica†

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In this work, material aspects of natural mica are studied. This work makes an attempt to analyze the dielectric properties of mica. Several investigations have been carried out on natural mica specimens such as optical absorbance, AC and DC electrical characteristics. Optical reflectance of mica sheet with plane polarized monochromatic light shows distinct difference with conventional theoretical result. The AC and DC conductivities are also measured. There exists a clear difference in DC characteristic for presence and absence of stray electromagnetic fields. The XRD and impedance spectroscopy analysis are also carried out for further analysis. The results obtained from the optical reflectance characteristics using polarized light indicate LHM behaviour as may be found in a meta-material on white mica. However black mica exhibits no such nature. Micro-structural and electrical analysis shows that it is a nano-structured layered material.

Key Words: Meta material, Impedance spectroscopy, Optical reflectance, Left-handed Maxwellian material.

INTRODUCTION

Ordinary dielectric materials follow right handed Maxwellian system in regard of electrodynamics *i.e.* electric field vector **E**, magnetic field vector **H** and propagation vector **k** form a right handed triplet. On the other hand in a left handed Maxwellian system (LHMS) **E**, **H**, **k** vectors form left handed triplet. The materials for which both real part of permittivity ε and permeability μ are negative for a given frequency range which follow left handed Maxwellian system[1]. Such materials may exhibit negative refraction. Later on, it has been found that there may be four different types of left handed Maxwellian system of type II and type III materials show positive refraction in spite of the presence[2] of negative ε and μ. It is important to investigate the naturally occurring material for their left handed meta-material like properties at optical frequency.

In the present work authors investigated different properties of natural 'mica'. Mica is naturally built anisotropic layered structured material. It is the general name of a series of silicate minerals. These minerals have highly perfect basal cleavages. The physical structure of mica consists of 2:1 layers[3], which are separated by interlayer cations like K^+ or Na^+. Al, Fe and Si are the major elements of mica. Some of the well known micas are muscovite, phologopite, biotite, lepidolite and vermiculite. Only the first two has commercial demands [4,5]. Different synthetic fluorophlogopites has also been produced to increase dielectric strength, high resistance to heat, flexibility and to reduce unit cost[5]. Mica is an important material due to its excellent mechanical and electrical insulating property. Moreover its many other applications are yet to be investigated.

In this present work XRD, electrical, dielectric and optical measurements were carried out over natural mica specimens. In an earlier communication[6] authors have investigated some optical properties of natural mica. The optical behaviour of mica is found to be fascinating[6]. From the results of present simple investigation it has been found that some optical and dielectric characteristics of the specimen are very much different from that of ordinary material. The details of the measurement, results and analysis are given in the following subsections. In the following a brief account of theoretical aspects of left-handed Maxwellian system along with the experimental results of present work are discussed.

Dielectric nature of an anisotropic medium: In an anisotropic dielectric system the principal dielectric constant of the material is given by the equations:

$$D_x = \varepsilon_x E_x, \quad D_y = \varepsilon_y E_y, \quad D_z = \varepsilon_{z.} E_{z.} \qquad (1)$$

where, ε_x, ε_y, ε_z are called the principal permittivity.

Transparent anisotropic dielectrics may be classified as follows, a) Optically isotropic, b) Optically uniaxial, c) Optically biaxial[7]. Mica is popularly known as optically biaxial in nature[8]. It has three different principal dielectric constants. Three different refractive indices are: $n_x = 1.552$, $n_y = 1.582$, n_z

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= 1.588. Though refractive indices of mica depend on wavelength the reported values of refractive index are typical one[8]. However, it was not mentioned about the type of mica was used in the experiment.

Left handed Maxwellian system: The electromagnetic propagation through a medium is possible if the product $\mu\,\varepsilon$ is positive. From this it can be concluded that for propagation to be possible either (a) μ, ε both positive (this occurs in ordinary material.) or (b) μ, ε both negative. This is the case of left handed Maxwellian system (LHMS). In a left handed system **E**, **H**, **k** form left handed triplet. In a left handed material the direction of **k** is opposite to the direction of pointing vector **S**[1]. Negative refractive index is the characteristics of left handed media for a left handed Maxwellian system. However a left handed Maxwellian system is also possible where n is positive (since in that case also ε, μ both are negative). It has been reported that four types of left handed Maxwellian system are possible from which type II and type III left handed Maxwellian system show positive refractive index[2]. If an electromagnetic wave passes through a boundary separating one right handed medium ($\varepsilon_1 > 0$, $\mu_1 > 0$, $n > 0$) and one left handed medium ($\varepsilon_2 < 0$, $\mu_2 < 0$, $n > 0$) fresnel equations are modified[2].

Case: I Electric vector E is perpendicular to the plane of incidence:

$$R_{\perp} = \left(\frac{E_r}{E_i}\right)_{\perp} = \left[\frac{\sin\theta_2\cos\theta_1 + \frac{\mu_1}{|\mu_2|}\sin\theta_1\cos\theta_2}{\sin\theta_2\cos\theta_1 - \frac{\mu_1}{|\mu_2|}\sin\theta_1\cos\theta_2}\right]^2 \qquad (2)$$

Case: II Electric vector E is parallel to the plane of incidence:

$$R_{\parallel} = \left(\frac{E_r}{E_i}\right)_{\parallel} = \left[\frac{-\frac{\mu_1}{|\mu_2|}\sin\theta_1\cos\theta_1 - \sin\theta_2\cos\theta_2}{\sin\theta_2\cos\theta_2 - \frac{\mu_1}{|\mu_2|}\sin\theta_1\cos\theta_1}\right]^2 \qquad (3)$$

where, $R_{\perp}$ and $R_{\parallel}$ are the intensity or energy reflectance for perpendicular and parallel polarization respectively. The results obtained from Eqns. 2 and 3 are irrational since in these equations, the reflectances are more than one for different angle of incidences. Hence to make R + T = 1, T (respective transmittance coefficient) becomes negative. The consequence of the result is the continuous energy gain from the medium, which is against the second law of thermodynamics. This ambiguity can be removed if ε and 7μ are taken as complex quantity in the equations. Following[2] the value of negative refractive index (r.i) for the system given by Eqn. 3 is estimated to be n = 1.2 when $\mu_1 = -\mu_2$. It appears from the work[2] that the value of refractive index, n = 1.2, is in general and irrespective of material and wavelength of light used.

Sample: Mica (phlogopite) in sheets form was collected from Kodarma region. The cut out portion of the mica sheet was directly employed as experimental specimens for different experiments.

EXPERIMENTAL

The different experimental probes used in the present investigation were as follows. XRD of mica was carried out to investigate its micro-structure by using Rigaku Miniflex, Japan with CuK$_\alpha$ line (λ = 1.541 nm), 2θ value ranging from 5° to 120° with sampling width 0.03 degree. The optical reflectance measurement was carried out using specially designed optical spectrometer, an indigenous set up in which a monochromatic sodium light was used as a source and a polarizer was used at collimator end of a spectrometer to get plane polarized light. The cross-wire of the spectrometer was replaced by a light dependent resistive wire to produce equivalent current proportional to the light intensity. The currents from the wire were recorded by Keithley 2400 (USA) source meter to measure equivalent intensity. The electric current equivalent of reflected light intensity for different angle of incidence of the plane polarized light was noted. Experiment was carried out for the polarization parallel to the plane of incidence. The angular resolution of the optical set-up was about ~20″. DC voltage-ampere (I-V) characteristic of the sample was measured by PC interfaced Keithley 2400 source meter. For this measurement the sample was taken between two copper electrodes. AC impedance measurements of the bulk specimen between two copper electrodes were carried out using LCR meter, HIOKI Hitester (Japan) model 3522-50 between frequency range 1 to 100 kHz.

RESULTS AND DISCUSSION

The microstructure of mica was examined by XRD analysis. Fig. 1 shows the XRD pattern of the specimen. Condition for diffraction from set of planes can be obtained from Bragg's law:

$$2d\sin\theta = n\lambda \quad \text{with} \quad n = 0, 1, 2 \qquad (4)$$

where, d is the separation between successive planes, n is order of reflection; θ is the angle of incidence of X-ray.

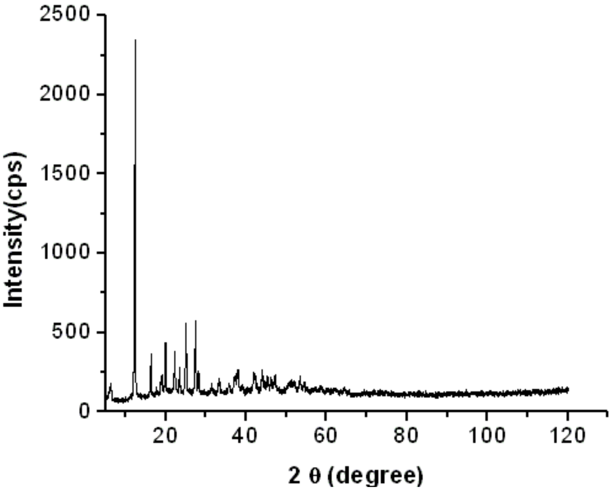

Fig. 1. XRD of mica specimen

Considering n = 1 and using the value of X-ray wavelength λ, different d value (for different specular angle θ) is estimated by:

$$d = \lambda/2\sin\theta \qquad (5)$$

For the second peak (corresponding $2\theta = 12.410$ and $n = 1$) using eqn. 5, 'd' value is estimated to be 7.124 Å. With same value of d and taking second and third higher order of reflection 2θ are estimated to be 24.96° and 37.85° respectively. 24.96° correspond to 8th and 37.85° correspond to 17th peak. Following the same process peak number 13 (corresponding $2\theta = 38.02°$) is the second higher order of peak no. 3 (corresponding $2\theta = 16.34°$) for d = 5.418 Å. Peak number 14 (corresponding $2\theta = 35.76°$) and peak number 28 (corresponding $2\theta = 55.03°$) are the respective second and third higher orders of peak no. 4 (corresponding $2\theta = 17.66°$) for d = 5.016 Å. Peak no. 19 (corresponding $2\theta = 40.80°$) is the second higher order of peak no. 6 (corresponding $2\theta = 19.97°$) for d = 4.657 Å. From the obtained values it is clear that for a definite d there are series of peaks, which is the manifestation of layered structure with unequal separation of layers.

From Fig. 1 the particle size 't' is estimated following Scherrer formula[9] given by eqn. 6. Where, B is the full width at half maximum intensity of the diffraction curves (measured in radian), θ_B is the angle of maximum intensity for a peak and θ_1, θ_2 are the angles at half maxima position.

$$t = \frac{0.9\lambda}{B\cos\theta_B} \qquad (6)$$

The estimated sizes of the particles using eqn. 6 are found between range 13 to 28 nm. Hence it may be emphasized that mica layers contain nano sized particles.

Fig. 2 shows the variation of optical reflectance with angle of incidence for parallel field polarization. The figure shows a verification of Fresnel's equation on mica surface. Graph C, in Fig. 2, are standard electro-magnetic theoretical results on glass surface representing Fresnel equations. Graph D (Fig. 2), is the experimental analogue of graph C. In Fig. 2 graph A is the representation of eqn. 3. $\varepsilon_2 = -1.5\varepsilon_1$ and $\mu_2 = -\mu_1$ is used to plotting the graph A. The experimental results on mica are shown in graph B of Fig. 2. This figure shows that Brewster angle for glass is close to 57.8°. The value is comparable to theoretical estimation on prism glass, which is about 58.3°. In fact one may entrust the accuracy of the developed optical reflectance measurement system. The same figure shows that, for mica, the extinction of parallel polarization of **E** vector is absent in the reflected ray. Hence there is no Brewster's angle for mica. Thus the results on mica summarized in the figures show an optical behaviour different from that measured over glass surface/ordinary material. But the results on mica specimen, graph B in Fig. 2, are in fact similar to those obtained from left handed Maxwellian system theoretical results, graph A in Fig. 2, on type II and III materials[2]. The estimated value of refractive index was found to be n = 1.19. The over all results obtain are in qualitative agreement with theoretical result[2]. The agreement between the results appeared to be a conjecture. Obtained experimental graph on mica shows a finite peak at the anti-Brewster angle corresponding to maximum reflectance however corresponding theoretical peak shows an infinite intensity[2]. The present investigation on mica specimen shows $R < 1$ in contrast to theoretical graph, computed from eqn. 3, showing intensity Reflectance $R >> 1$. The later must be ruled out in practice unless or otherwise the material pumped out energy from its own bulk without any work, which is against the second law of thermodynamics.

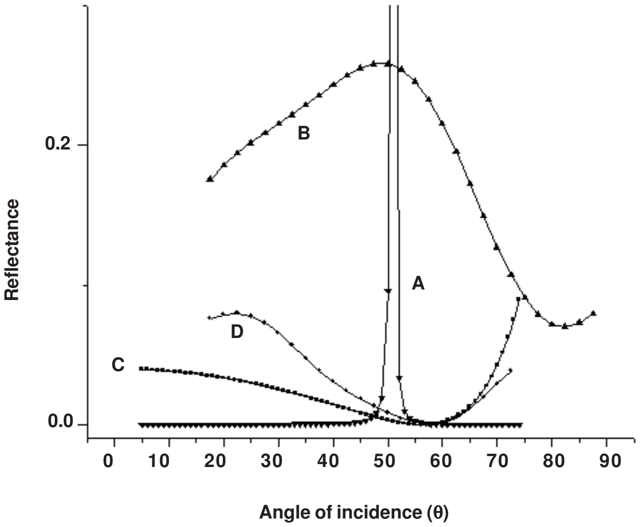

Fig. 2. Plot of reflectance of white mica surface with angle of incidence for electric field parallel to the plane of incidence. A-theoretical curve computed from eqn. (3) and B-experimental curve of mica specimen, C- theoretical curve of glass and D-experimental curve of prism glass

Fig. 3 shows DC current-voltage characteristics of mica specimen when the field lines are along the surface of the sample. Inset graph in the Fig. 3 represents the I-V characteristics of mica specimen when the field lines are transverse to the surface of the sample. The results of DC experiment once again establish the anisotropic physical properties represented by rank two tensors. The conductivity of the sample increases -100 times in the former case than latter. The DC I-V plots have a closer similarity with that obtained from materials that contain nano sized grains.

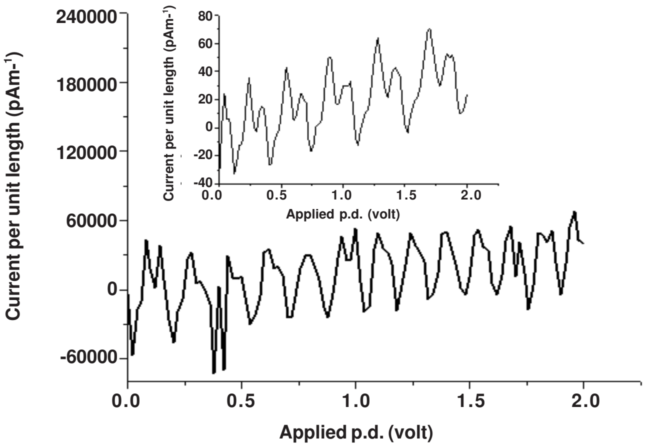

Fig. 3. Current-voltage characteristics of mica specimen when the applied field is along the surface of the sample. Inset figure shows the same when the field lines are transverse to the specimen surface

The results of impedance spectroscopy are summarized by Fig. 4. It compares the conductivity dispersion of white and black micas and show that bulk electrical conductivity of both the varieties of mica are mostly electronic. Fig. 5 compares the variation of relative dielectric constants of black and white mica with the frequency of the impressed electric field.

Both white and black variety of mica exhibits very high static (low frequency limiting value of corresponding AC value) dielectric constant. Perhaps black mica has lower dielectric constant compared to that of white mica. However black mica does not exhibit left hand Maxwellian character in optical reflectance experiment.

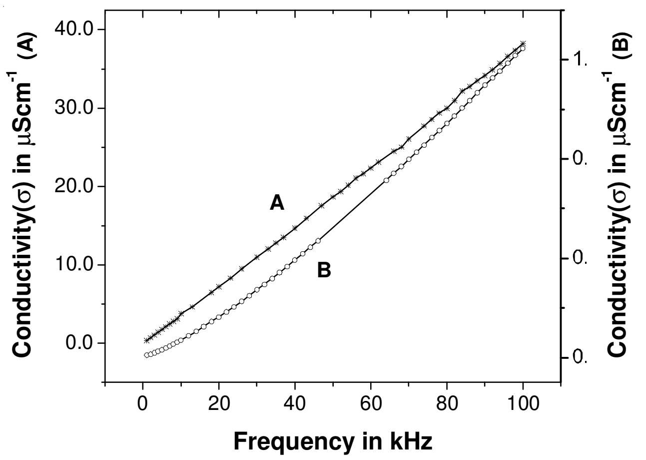

Fig. 4. AC conductivity characteristics of mica specimen with frequency shift. A-corresponds to white mica (on left scale). B-corresponds to black mica (on right scale)

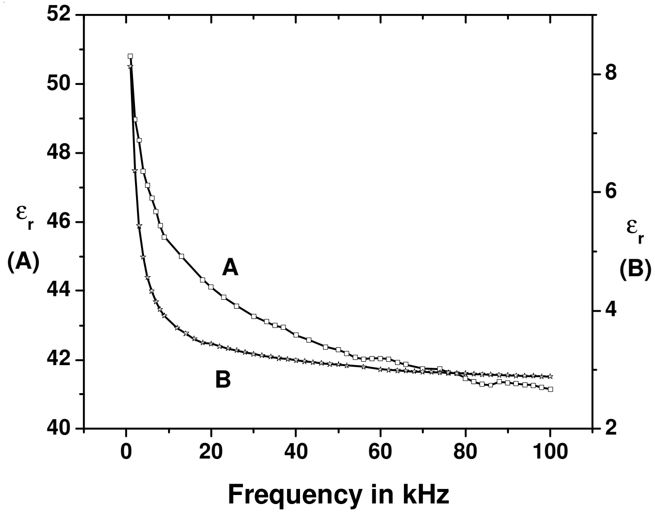

Fig. 5. Variation of relative dielectric constant of mica specimen with frequency of impressed AC field. A-corresponds to white mica (on left scale). B-corresponds to black mica (on right scale)

Conclusion

The experimental mica specimen is a layered structured material containing nano particles. It exhibits a feature different from that of an ordinary material like glass. The outcome of present investigation indicates that the experimental mica specimen is a left handed Maxwellian system (type II or III). The results of ac experiment shows that natural mica has a very large dielectric constant and that decreases sharply with increase in frequency of impressed ac field. The possibility of negative dielectric constant may not be ruled at very high frequency.

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