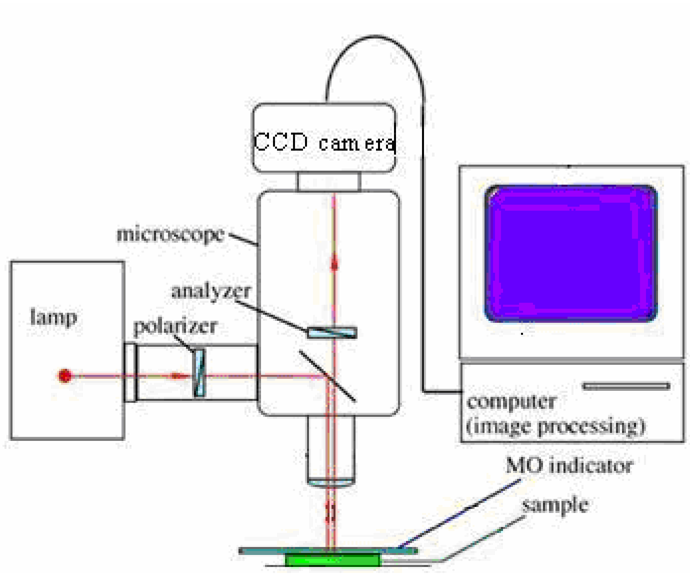
Project Report

Project report : FA4869-06-1-0073 (AOARD – 064054)
Title : Imaging the spatial distribution of transport currents and the phenomenon of nanoscale phase separation phenomenon in CMR materials.
Principle Investigator (PI): Dr. Satyajit Banerjee, Assistant Professor, Dept. of Physics, IIT Kanpur

Summary of the progress over the past one year:

The aim of the proposal was to develop a magneto-optics imaging (MOI) set up which will enable the direct imaging of transport current distribution inside a variety of materials. The primary objective of my proposal was to enhance the sensitivity of the existing magneto-optical imaging setup developed in my (PI) laboratory to optically image the self fields generated by transport currents sent through materials. Based on the above objective it was planned to apply this technique to investigate fundamental issues like magnetic phase separation in colossal magneto resistive materials as well as to investigate possible applications like nondestructive detection of stress and fatigue in materials. As of now, we have succeeded in enhancing the sensitivity of our MOI setup so as to enable the imaging of transport currents down to 20 mAmps. We have also succeeded in characterizing the magnetic ground state in a particular CMR material, which subsequently we plan to investigate with our MOI setup.

Progress made in detecting magnetic field generated by transport currents:



Brief introduction to our magneto – optical imaging (MOI) system: The Magneto-optical imaging (*MOI*) technique for the study of magnetic field distribution inside materials is based on the Faraday Effect. The Faraday effect is the phenomenon of rotation of linearly polarized light in certain special crystals when the magnetic field in on the crystals is in the direction of the propagation wave vector of light. The rotation angle (θ_F) is given by the expression:

$$\theta_F = V B_z d ;$$

where V is the Verdet constant, B_z is the component of the magnetic field along the propagation wave vector of the light and d is the optical path length in the crystal. A schematic of our magneto-optical imaging setup is shown above (various parts in the setup have been labeled). The analyzer shown in the figure

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14. ABSTRACT
The aim of the proposal was to develop a magneto-optics imaging (MOI) set up which will enable the direct imaging of transport current distribution inside a variety of materials. The primary objective of the proposal was to enhance the sensitivity of the existing magneto-optical imaging setup developed in the PI?s laboratory to optically image the self fields generated by transport currents sent through materials. Based on the above objective it was planned to apply this technique to investigate fundamental issues like magnetic phase separation in colossal magneto resistive materials as well as to investigate possible applications like nondestructive detection of stress and fatigue in materials. As of now, success has been achieved in enhancing the sensitivity of our MOI setup so as to enable the imaging of transport currents down to 20 mAmps. Furthermore, characterization of the magnetic ground state in a particular CMR material has been performed, which subsequently will be investigated with the MOI setup.

15. SUBJECT TERMS
Nanoscale phase separation, Nanoscale phase separation, CMR materials, CMR materials, Magneto-optical imaging , Magneto-optical imaging

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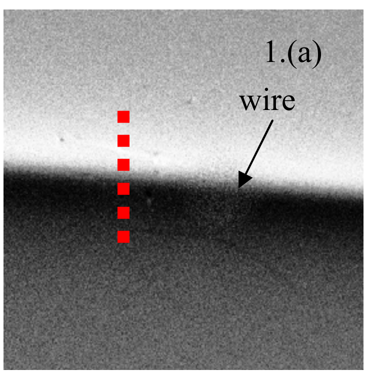
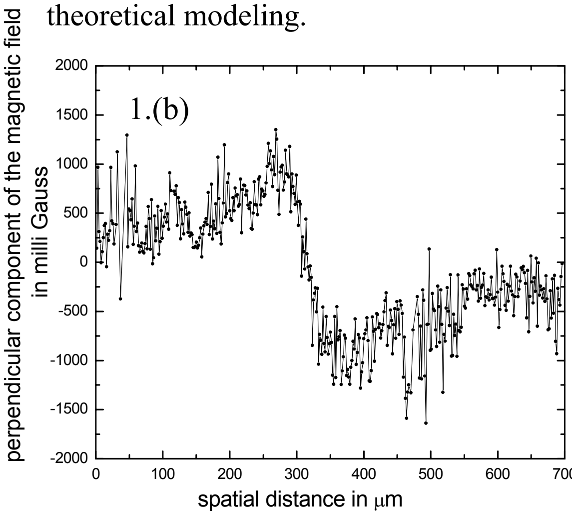
above is placed at right angles to the linear polarizer. The rotated linearly polarized light goes onto a very high sensitivity CCD camera (85% quantum efficiency at 550 nm, 16 bit), which is interfaced with the computer. The intensity of faraday rotated light ($I=I_0 Sin(\theta_F)$) distributed over the sample surface as recorded by the CCD camera can be calibrated to reveal the local field B_z distributed on the sample surface. In this conventional mode of operation, the maximum magnetic field sensitivity provided by the MOI system is of the order of few Gauss. Our aim was to modify the existing MOI system so as to provide us a much higher field sensitivity.

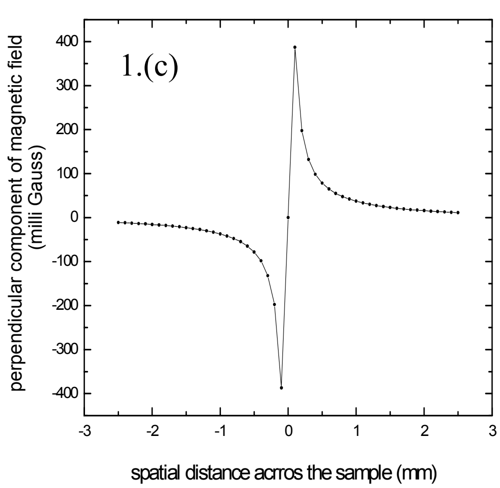
Brief highlight of results: The focus of my project is to use the MOI system to image the magnetic field associated with transport currents (self field). However in many situations the current which can be passed through the material is usually small, in the milli-Amps range, which implies that the self field which is associated with these small currents is of the order of few milli – Gauss (*mG*). Such small field (~O(*mG*)) is definitely below the sensitivity range of our conventional MOI setup, which has a sensitivity ~ O(*Gauss*).

We implemented a novel scheme of modulating the current which is being sent through the sample. Due to the modulation in current, the associated self field also modulates the faraday rotated light intensity $I=I_0 Sin(\theta_F)$ (as θ_F. is modulated with the self field of the current). The intentionally modulated faraday rotated light intensity was captured synchronously with a CCD camera (a procedure akin to lockin type detection technique of small signals). We obtained via this sensitive technique the ability of detect faraday rotations corresponding to very low magnetic fields (B_z) which were of the *order of few mGauss*.



In the adjoining figure 1.(a) we show the magneto-optical image of the self-field generated across a 25 micron thick copper wire carrying a current of 20 mAmps (*Please note this data is as of now unpublished*). Shown in figure 1.(b) below is the line scan across the red dashed line in fig.1.(a). Figure 1.(b) represents the field distribution around the copper wire (which is the gray line seen in between the bright white and black regions in Fig.1.(a)) as inferred from the magneto-optical image. Fig. 1.(c) is a graph of the magnetic field distribution obtained from the Biot Savarts law for a straight wire carrying a current of 20 mAmps. Notice the reasonably good qualitative match between the measured field distribution in Fig.1(b) and the theoretical expected field distribution in Fig.1(c). For a more accurate fit we are refining the theoretical modeling.





With the present success of our technique, developed under this project we are in the process of exploring the current distribution in a variety of materials like CMR materials as proposed under my project.
We would like to mention that the manuscript based on the above work is already under preparation and we expect to submit this manuscript to an international journal by adding some more work to in within the next two months. We will be acknowledging the funding provided by AOARD for this work

Progress on investigating magnetic phase separation in colossal magneto resistance (CMR) materials: Through my proposal I wanted to investigate how the magnetic phase separation would manifest itself in modifying the transport properties of CMR materials. It is not well investigated as to how the magnetic phase separation at microscopic length scales affects the bulk transport properties in CMR materials. We planned to investigate this problem using our MOI based transport current imaging technique on a variety of CMR materials under different conditions. The MOI technique would enable us to image the local transport current distribution which would reveal variations in local transport properties of the CMR materials associated with magnetic phase separation. However before embarked on this project, it was imperative to determine the magnetic ground state of the CMR materials to be investigated.

We investigated the magnetization properties of $La_{0.9}Mn_{0.1}CaO_3$ via a variety of ac susceptibility and dc magnetization measurements and FMR measurements which were possible to do by the grants obtained from our proposal. We have been able to investigate the magnetic phase separation by comparing magnetization response in bulk (single crystals) and nanopowders of $La_{0.9}Mn_{0.1}CaO_3$. The magnetic ground state in bulk single crystals form of the above material is predominantly an mixed antiferromagnetic + ferromagnetic state which becomes predominantly ferromagnetic like in the nanopowdered form. We have found that the ferromagnetism in the $La_{0.9}Mn_{0.1}CaO_3$ nano-powders gets suppressed due to super-paramagnetic effect which tends to disorder the ferromagnetic alignment of spins. We have published this study in *Journal of Non-Crystalline Solids 353 (2007) 817–819*, and we have also sent a more detailed version of our investigation to an international journal for publication. Having uncovered the nature of the magnetic ground state and phase separation in a particular CMR material, the stage is set for our MOI based transport current imaging technique to be applied to the single crystals of $La_{0.9}Mn_{0.1}CaO_3$. To investigate CMR materials we need a temperature range of 70 K – 200 K. We are in the process of designing a special variable temperature cryostat with optical access in which MOI can be performed.

Paper published so far:

1. Nano-particles of La0.9Ca0.1MnO3 manganite: Size-induced change of magnetic ground state and interplay between surface and core contributions to its magnetism; E. Rozenberg, **S.S. Banerjee** , I. Felner , E. Sominski , A. Gedanken; *Journal of Non-Crystalline Solids 353 (2007) 817–819.*

Manuscript Submitted

1. Disorder Induced Phase Coexistence in Bulk Doped Manganites and its Suppression in Nanometer Sized Crystals: The Case of $La_{0.9}Ca_{0.1}MnO_3$; E. Rozenberg,A. I. Shames, G. Jung, M. Auslender, G. Gorodetsky, I. Felner, Jaivardhan Sinha, **S. S. Banerjee**, E. Sominski, A. Gedanken, and Ya. M. Mukovskii (Submitted).

Manuscipts under preparation

1. A manuscript from my Lab. is under preparation which will be reporting use of MOI for imaging transport currents inside materials.

Talks given where the funding from AOARD was acknowledged:

1. Colloquium at Tata Institute of Fundamental Research, Mumbai, India
   Title: Advances in Magneto-optical imaging.
   Date: 18^{th} July, 2007.

2. Instabilities in superconductors and mapping megagauss magnetic fields associated with laser plasma interactions. S. N. Bose National Center for Basic Sciences, Kolkata, 30^{th} March, 2007.