www.amlett.com, www.vbripress.com/aml, DOI: 10.5185/amlett.2015.5958

Published online by the VBRI Press in 2015

# Estimation of magnetic interactions in substituted Mg-Mn ferrites synthesized via citrate precursor technique

# Gagan Kumar<sup>1\*</sup>, Virender Pratap Singh<sup>1</sup>, Arun Kumar<sup>1</sup>, Jyoti Shah<sup>2</sup>, Shalendra Kumar<sup>3</sup>, B.S. Chauhan<sup>1</sup>, R.K. Kotnala<sup>2</sup>, M. Singh<sup>1</sup>

<sup>1</sup>Department of Physics, Himachal Pradesh University, Shimla 171005, India

<sup>2</sup>CSIR-National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi 110012, India

<sup>3</sup>Department of Physics, Pohang University of Science and Technology, Pohang 790784, Republic of Korea

\*Corresponding author. Tel: (+91) 9816418069; E-mail: bhargava\_phy\_hpu@yahoo.co.in

Received: 03 March 2015, Revised: 25 May 2015 and Accepted: 01 June 2015

# ABSTRACT

We investigated the effects of  $In^{3+}$  and  $Co^{2+}$  substitutions on the structural and magnetic properties of Mg-Mn ferrites. The cation distribution technique was taken into account to estimate the magnetic interactions. Cation distribution was also used to investigate the ionic radii of tetrahedral and octahedral sites, oxygen positional parameter, site bond as well as edge lengths, bond lengths and bond angles. The ionic radius of tetrahedral site and octahedral site was observed to increase with the incorporation of  $In^{3+}$  and  $Co^{2+}$  ions respectively. Theoretical lattice parameter was observed to increase with the substitution of  $In^{3+}$  and  $Co^{2+}$  ions.  $In^{3+}$  substitution resulted in weakening of super-exchange interactions while in  $Co^{2+}$  substituted Mg-Mn ferrites, anisotropy was observed to play a decisive role in addition to bond lengths and bond angles. Copyright © 2015 VBRI Press.

Keywords: Ferrites; cation distribution; oxygen parameter; bond lengths; bond angles.

# Introduction

Magnetism has been a human curiosity for nearly three thousand years and evolved as one of the most interesting and fascinating branch of science and technology. Although many famous scientists tackled the phenomenon of magnetism from the theoretical side it is mainly 20<sup>th</sup> century physicists who must take the credit for giving a proper description of magnetic materials and for laying the foundations of modern technology. Ferrimagnetic substances exhibit a substantial spontaneous magnetization at room temperature, just like ferromagnetic, and this fact alone makes them industrially important. Ferrites are one of the fascinating ferrimagnetic materials and are significant from application point of view. Ferrites are known to be appealing due to their good magnetic properties, high electric resistivity, low eddy current loss and low dielectric loss [1]. The high resistivity of ferrites makes them suitable for microwave applications. Ferrite materials are extensively used in inductors and transformers in telecommunication industry, antenna rods, loading coils, deflection yokes, choke coils, electromagnetic interface (EMI), power transformer, splitter applications, satellite communication, sensors, magnetic resonance imaging (MRI), audio and video recording heads, magnetic fluids and hyperthermal cancer treatment [2]. Therefore, the

diversity of applications makes ferrites an active area of research [3-5].

Mg-Mn ferrites are well known technological materials finding applications in various electrical and magnetic devices. The importance of Mg-Mn ferrites lies in their magnetic properties and low electrical conductivity which allow electromagnetic waves to propagate in the medium and make them suitable for applications in microwave devices. Mg-Mn ferrites are widely used in the construction of non-reciprocal devices at microwave frequencies such as circulators, gyrators and phase shifter.

In addition to this, they are widely used in computer memory chips, magnetic recording media, and fabrication of radio frequency coils, transformers cores and rod antennas [6-9].

In ferrites, the separation between the cations is large therefore the exchange interaction takes place by the participation of oxygen 'anions' and is called superexchange interaction. Since in ferrites magnetic ions occupy (A) and (B) sites, so there are three possible superexchange interactions namely [10]: A-A interaction, B-B interaction and A-B interaction. A-B interaction heavily predominates over A-A and B-B interactions. A-B interaction aligns all magnetic spins at A-site in one direction and those at B-site in opposite direction thus constitute two saturated and magnetized sublattices at 0 K. Net magnetization of lattice is, therefore, the difference between magnetization of the B and A sublattices.

It is reported by V. K. Lakhani et al [11] that the spinel ferrites are known to have some favorable distances and angles in between the ion pairs at which the magnetic interactions are much effective, therefore, in the present work we have made a theoretical attempt based on the cation distribution to get an information about the effects of  $In^{3+}$  and  $Co^{2+}$  ions on the super-exchange interactions in Mg-Mn ferrites.

## Experimental

#### Material Synthesis

The ferrite series  $Mg_{0.9}Mn_{0.1}In_xFe_{2-x}O_4$  and  $Mg_{0.9}Mn_{0.1}$ Al<sub>0.3</sub>Co<sub>z</sub>Fe<sub>1.7-z</sub> O<sub>4</sub> (x = 0.0, 0.1, 0.3 & 0.5, z = 0.3, 0.5 & 0.7) were prepared by citrate precursor technique [**12-14**] using hydrated nitrates of the constituent elements of purity  $\geq$  98%.

The chemicals used were as: (a) Mg  $(NO_3)_2.6H_2O$ , (b) Mn  $(NO_3)_2.4H_2O$ , (c) Al  $(NO_3)_3.9H_2O$ , (d) In  $(NO_3)_3.5H_2O$ , (e) Co  $(NO_3)_3.6H_2O$  and (f) Iron was in the form of iron citrate  $C_6H_5O_7Fe.3H_2O$ .

The solid state reactions used for the preparation of the samples were as:

were present in the samples. In order to confirm the homogeneity of the samples scanning electron micrographs were taken.

# **Results and discussion**

X-ray diffraction pattern indicating (*hkl*) values of each peak for the ferrite compositions ( $Mg_{0.9}Mn_{0.1}In_{0.5}Fe_{1.5}O_4$  and  $Mg_{0.9}Mn_{0.1}Al_{0.3}Co_{0.5}Fe_{1.2}O_4$ ) are shown in **Fig. 1**. The typical SEM images for ferrite compositions ( $Mg_{0.9}Mn_{0.1}In_{0.5}Fe_{1.5}O_4$  and  $Mg_{0.9}Mn_{0.1}Al_{0.3}Co_{0.5}Fe_{1.2}O_4$ ) are shown in **Fig. 2**.

The particle size of the samples was calculated from the broadening of the X-ray diffraction peaks using the Debye-Scherrer equation for the Lorentzian peak [15],

$$D = \frac{0.9\lambda}{\beta \cos \theta} \tag{1}$$

where, *D* is the particle size,  $\beta$  is the full width at half maximum (FWHM) of the (311) peak,  $\lambda$  is the X-ray wavelength (1.54 Å) and  $\theta$  is the angle of diffraction. The average value of particle size was observed to be ~0.5 µm.

 $\begin{array}{l} (1) \ 0.9 \ [Mg(NO_3)_2.6H_2O] + 0.1[Mn(NO_3)_2.4H_2O] + x[In(NO_3)_3.5H_2O] + (2-x)[C_6H_5O_7Fe.3H_2O] \rightarrow [Mg_{0.9}Mn_{0.1}In_x \ Fe_{2.x}O_4]; \ x = 0.0, \ 0.1, \ 0.3 \ \& \ 0.5. \\ (2) \ 0.9[Mg(NO_3)_2.6H_2O] + 0.1[Mn(NO_3)_2.4H_2O] + 0.3[Al(NO_3)_3.9H_2O] + z[Co(NO_3)_3.6H_2O] \ + (1.7-z) \ [C_6H_5O_7Fe.3H_2O] \end{array}$ 

The quantities of the reagents required for each composition were calculated from the above solid state reactions. In the present method, the required quantity of iron citrate was dissolved in ~50 ml of distilled water by heating to 40°C with constant stirring. For the In<sup>3+</sup> doped series, required amount of magnesium nitrate, manganese nitrate and indium nitrate were dissolved in ~ 40-50 ml of distilled water by heating to 40°C and constant stirring. The solution of these nitrates was added to the solution of iron citrate, and ~2-3 gm of citrate acid. The composite solution was heated at 40°C for about an hour with constant stirring. The precursor mixture is then heated to 40°C with constant stirring, to allow the water to evaporate, leaving behind a dried mass in the form of brown coloured glassy material containing the constituent metal ions homogeneously mixed together at the atomic level. The dried mixture was calcined for 2h at 500 °C at the rate of 250 °C/h to obtain ferrite powder. The same procedure was followed for Co<sup>2+</sup> substituted ferrite series.

#### **Characterizations**

The single- phase nature of the prepared samples was checked by X-ray diffraction studies, which were made by Cu-K<sub>a</sub> radiation of wavelength 1.54 Å using Riga Ku-Denki X-ray diffractometer. The cation distribution was obtained from the X-ray diffraction and magnetization technique [14].

The observed diffraction lines were found to correspond to those of standard pattern of Mg-Mn ferrite with no extra lines, indicating thereby that the samples have a single phase cubic spinel structure and no unreacted constituents



Fig. 1. XRD patterns for  $Mg_{0.9}Mn_{0.1}In_{0.05}Fe_{1.95}O_4$  and  $Mg_{0.9}Mn_{0.1}Al_{0.3}Co_{0.05}Fe_{1.65}O_4$  ferrites.

Using the cation distribution data [14], the mean ionic radius of the tetrahedral site  $(r_A)$  and octahedral site  $(r_B)$  is calculated by employing the relations those reported in our previous work [15] and the variations of ionic radius at tetrahedral  $(r_A)$  as well as octahedral  $(r_B)$  sites are shown in **Fig. 3 (a, b)**.





Fig. 2. SEM micrographs for  $Mg_{0.9}Mn_{0.1}In_{0.05}Fe_{1.95}O_4$  and  $Mg_{0.9}Mn_{0.1}Al_{0.3}Co_{0.05}Fe_{1.65}O_4$  ferrites.



Fig. 3. Variation of ionic radii of tetrahedral and octahedral sites with (a)  $In^{3+}$  and (b)  $Co^{2+}$  content.

It was observed that with the substitution of  $In^{3+}$  ions the ionic radius of tetrahedral site was increased while a very small increase in radius of octahedral site was observed. In Co<sup>2+</sup> substituted Mg-Mn ferrite series an increase was observed for radius of octahedral site and the radius of tetrahedral site was noticed to decrease first and then increased. These variations can be correlated to the difference in ionic radii of involved ions [16] and their site preferences [14]. Since  $In^{3+}$  ions prefer to occupy tetrahedral site and have ionic radius (0.91 Å) bigger than  $Fe^{3+}$  ions (0.67 Å) therefore its incorporation has resulted an increase in radius of tetrahedral site. In a similar manner the variation in radius of octahedral site with the incorporation of  $Co^{2+}$  ions can be explained as it has also bigger ionic radius (0.89 Å) as compared to radius of  $Fe^{3+}$ ions. The theoretical lattice parameter ( $a_{th}$ ) is calculated by using following relation [17]:

$$a_{th} = \frac{9}{3\sqrt{3}} \left[ (r_A + R_o) + \sqrt{3}(r_B + R_o) \right]$$
(2)

where  $r_A$ ,  $r_B$  are the mean ionic radius of tetrahedral (*A*) and octahedral *B* sites respectively while  $R_o$  is the radius of oxygen ions (1.32 Å).Variation of theoretical lattice parameter ( $a_{th}$ ) as a function of  $In^{3+}$  and  $Co^{2+}$  ion content is shown in **Fig. 4**. The theoretical lattice parameter was found to be increasing with the increasing substitution of  $In^{3+}$  and  $Co^{2+}$  ions. This is again because of the difference in ionic radii of the ions. Since the ionic radius of  $In^{3+}$  and  $Co^{2+}$  ions is large than that of  $Fe^{3+}$  ions therefore their substitution has resulted in an internal stress to make the lattice distorted.



Fig. 4. Variation of lattice parameter with  $In^{3+}$  and  $Co^{2+}$  content.

The O<sup>2-</sup> ions in the spinel structure are generally not located at the exact positions of the FCC sublattice. Their detailed positions are determined by oxygen positional parameter (*u*), which reflects adjustments of the structure to accommodate differences in the radius ratio of the cations in the A and B sites. Therefore, using values of  $a_{\rm th}$ , R<sub>o</sub>,  $r_{\rm A}$  and  $r_{\rm B}$  the oxygen positional parameter (*u*) is calculated with the help of following expressions [**18**]:

$$u^{\exists m} = \frac{\frac{1}{4}R^2 - \frac{2}{3} + \sqrt{\frac{11}{48}R^2 - \frac{1}{18}}}{2R^2 - \frac{2}{18}}$$
(3)

$$u^{\overline{4}3m} = \frac{\frac{1}{2}R^2 - \frac{1}{12} + \sqrt{\left(\frac{1}{48}R^2 - \frac{1}{18}\right)}}{2R^2 - 2} \tag{4}$$

$$u^{\overline{a}_{3m}} = \left[\frac{1}{a_{th}\sqrt{2}}(r_{A} + R_{o}) + \frac{1}{4}\right]$$
(5)

 $\frac{(B-Q)}{(A-Q)}$ . The bond lengths B-O and A-O are where, R =average bond lengths calculated based on the cation distribution; where  $B - O = \langle r_B + R_o \rangle$ and  $A-0 = \langle r_A + R_o \rangle$ . The calculated values are given in **Table** 1. Equation (3) gives 'u' assuming centre of symmetry at (1/4, 1/4, 1/4) for which  $u_{ideal} = 0.250$  Å (origin at *B*-site), while equations (4) and (5) give 'u' assuming centre of symmetry at (3/8, 3/8, 3/8) for which  $u_{ideal} = 0.375$  Å (origin at A-site). For these ideal values the arrangement of O<sup>2-</sup> ions corresponds exactly to a cubic closed packing, but this ideal situation is almost never realized and in actual spinel lattice this ideal pattern is slightly deformed [3]. The structure of the spinel has space group  $Fd3mO_7^h$  [19] and can be described as 32 oxide ions in nearly closed packing with eight of the 64 tetrahedral (A) sites and 16 of the 32 octahedral (B) sites normally occupied by cations. The oxygen parameter was observed to increase with the incorporation of  $In^{3+}$  and  $Co^{2+}$  ions.

Table 1. Variation of oxygen parameters for  $Mg_{0.9}Mn_{0.1}In_xFe_{2-x}O_4$  and  $Mg_{0.9}Mn_{0.1}Al_{0.3}Co_zFe_{1.7-z}O_4$  ferrites.

Ion	u <sup>3m</sup> (Å) (1/4, 1/4, 14)	u <sup>43m</sup> (Å) (3/8, 3/8, 3/8)		
content	Eq. 3	Eq. 4	Eq. 5	
In = 0.0	0.2597	0.386	0.387	
In = 0.1	0.2646	0.389	0.389	
In = 0.3	0.2652	0.390	0.392	
In = 0.5	0.2664	0.391	0.395	
Co = 0.3	0.2597	0.386	0.387	
Co = 0.5	0.2604	0.386	0.387	
Co = 0.7	0.2649	0.389	0.392	

The observed trend is suggesting that with the increasing substitution of  $In^{3+}$  and  $Co^{2+}$  ions the anions at *A*-sites are moving away from the cations at tetrahedral interstices due to the expansion of the tetrahedral interstices [**20**]. The bond lengths on the tetrahedral (*A*) site (shortest distance between *A*-site cation and oxygen ion) ( $d_{AX}$ ) as well as the octahedral (B) site (shortest distance between *B*-site cation and oxygen ion) ( $d_{BX}$ ), tetrahedral edge ( $d_{AXE}$ ), shared octahedral edge ( $d_{BXE}$ ) and unshared octahedral edge ( $d_{BXEU}$ ) were calculated by using the values of the lattice parameter and oxygen positional parameter of each ferrite by using the following relations [**21**]:

$$d_{AX} = \sqrt{3}a\left(u^{\overline{4}\,3m} - \frac{1}{4}\right) \tag{6}$$

$$d_{BX} = a \sqrt{\left(3u^{\frac{3}{3}m^2} - \frac{11}{4}u + \frac{43}{64}\right)} \tag{7}$$

$$d_{AXE} = \sqrt{2}a\left(2u^{43m} - \frac{1}{2}\right) \tag{8}$$

$$d_{BXE} = \sqrt{2a(1 - 2u^{4am})} \tag{9}$$

$$d_{BXEU} = a \sqrt{\left(4u^{43m^2} - 3u^{43m} + \frac{11}{16}\right)}$$
(10)

Variations of  $d_{AX}$ ,  $d_{BX}$ ,  $d_{AXE}$ ,  $d_{BXE}$  and  $d_{BXEU}$  with an increase in  $In^{3+}$  and  $Co^{2+}$  ion content are shown in **Fig. 5** and **Fig. 6** respectively.

It was observed that the bond length of unshared octahedral edge ( $d_{\text{BXEU}}$ ) does not changed with the addition

For z = 0.7 a decrease in the bond length of octahedral site was noticed and the same can be because for z = 0.7 the occupancy of cobalt on tetrahedral as well as octahedral site is comparable so due to migration of more Co<sup>2+</sup> ions to tetrahedral site as compared to z = 0.3 and 0.5 the expansion of tetrahedral site is resulting due to shrinkage of octahedral site. The observed variation in different bond lengths is reflecting the variation of tetrahedral and octahedral ionic radius.



Fig. 5. Variation of (a) site bond length and (b) site edge with  $In^{3+}$  content

The bond lengths between the cations and cations-anion are known to play a crucial role on the overall strength of different magnetic interactions (*A*-*B*, *A*-*A* and *B*-*B*). Therefore, in the present work we tried to evaluate the same to get information about the effect of  $In^{3+}$ , and  $Co^{2+}$  ions on the super-exchange interactions.

The inter-ionic distances between the cations  $(M_e - M_e)$  (b, c, d, e, and f) and between the cation and anion  $(M_e - 0)$  (p, q, r and s) were calculated by substituting the experimental values of lattice parameter (a) and oxygen positional parameters (*u*) in the following relations [21]:

$M_{e} = 0$	
$p = a\left(\frac{1}{2} - u^{3m}\right)$	(11)
$q = a \left( u^{3m} - \frac{1}{g} \right) \sqrt{3}$	(12)
$r = a \left( u^{3m} - \frac{1}{s} \right) \sqrt{11}$	(13)
$s = \frac{a}{3}\left(u^{3m} + \frac{1}{2}\right)\sqrt{3}$	(14)
$M_e - M_e$	
$b = \left(\frac{a}{4}\right)\sqrt{2}$	(15)
$c = \left(\frac{a}{2}\right)\sqrt{11}$	(16)

$$d = \left(\frac{a}{4}\right)\sqrt{3} \tag{17}$$

$$e = \left(\frac{a}{2}\right)\sqrt{3} \tag{18}$$
$$f = \left(\frac{a}{4}\right)\sqrt{6} \tag{19}$$



Fig. 6. Variation of (a) site bond length and (b) site edge with  $Co^{2+}$ content.

The bond angles  $(\theta_1, \theta_2, \theta_3, \theta_4 \text{ and } \theta_5)$  were calculated by simple trigonometric principle using the inter-ionic distances with the help of following formulae [11]:

$$\theta_1 = \cos^{-1} \left[ \frac{p^2 + q^2 - c^2}{2\pi q} \right]$$
(20)

$$\theta_2 = \cos^{-1} \left[ \frac{p^2 + r^2 - e^2}{2pr} \right]$$
(21)

$$\theta_{3} = \cos^{-1} \left[ \frac{2p^{2} - p^{2}}{2p^{2}} \right]$$
(22)  
$$\theta_{4} = \cos^{-1} \left[ \frac{p^{2} + s^{2} - f^{2}}{2p^{2}} \right]$$
(24)

The calculated values of inter-ionic distances between the cations (b, c, d, e and f) are shown in Fig. 7, while the inter-ionic distances between cation and anion (p, q, r and s) and bond angles are given in Table 2.

It can be observed from Fig. 7 that with the substitution of In<sup>3+</sup> and Co<sup>2+</sup> ions the inter-ionic distance between cations (b, c, d, e and f) is increasing. Since these distances are related to lattice parameter so the observed trend was expected. Further, from Table 2, the inter-ionic distance between cations and anions (q, r and s) was observed to be increasing with the increasing substitution of In<sup>3+</sup> and Co<sup>2+</sup> ions.



Fig. 7. Variation of inter-ionic distances between the cation-cation with (a)  $In^{3+}$  and (b)  $Co^{2+}$  content.

Table 2. Variation of inter-ionic distances between the cation-anion and bond angles for  $Mg_{0.9}Mn_{0.1}In_xFe_{2-x}O_4$  and  $Mg_{0.9}Mn_{0.1}$   $Al_{0.3}Co_zFe_{1.7-z}O_4$ ferrites.

с	Indium content				Cobalt content		
	0.0	0.1	0.3	0.5	0.3	0.5	0.7
p (Å)	2.02	1.98	1.98	1.99	1.99	2.01	1.99
q (Å)	1.96	2.03	2.05	2.09	1.94	1.97	2.05
r (Å)	3.75	3.89	3.93	4.01	3.71	3.77	3.92
s (Å)	3.68	3.71	3.74	3.78	3.64	3.68	3.74
$\theta_1$	122.21	120.66	120.46	120.07	122.14	122.01	120.59
$\theta_2$	139.99	134.19	133.55	132.22	139.99	139.11	133.87
$\theta_3$	94.7	97.29	97.64	98.34	94.7	95.05	97.47
$\theta_4$	126.37	126.94	126.8	126.94	126.16	126.51	126.8
$\theta_5$	71.4	67.6	67.17	66.3	71.4	70.79	67.36

298

The decreasing trend in  $\theta_1$ ,  $\theta_2$  and  $\theta_5$  is again suggesting the weakening of the A-B and A-A interactions and increase in  $\theta_3$  as well as  $\theta_4$  indicating the strengthening of the *B*-*B* interactions. Theoretical estimation of magnetic interactions based on cation distribution clearly predicted the weakening in super-exchange interactions with the incorporation of In<sup>3+</sup> and Co<sup>2+</sup> ions in the Mg-Mn ferrites. In fact, the obtained results for In<sup>3+</sup> series are in consistent with the Neel temperature obtained from susceptibility measurement and saturation magnetization behavior [16] but for Co<sup>2+</sup> substituted Mg-Mn ferrites the obtained prediction is not agreeing with the experimental results [13, 16]. The reason for this is that in present method we have just estimated the magnetic interaction based on the cation distribution but in case of cobalt anisotropy also plays a very important role. In Co<sup>2+</sup>, the crystal field is not able to remove the orbital degeneracy and the orbital moment is of the same order of magnitude as the spin moment due to which it is known to have large anisotropy [10, 16].

## Conclusion

Effects of  $In^{3+}$  and  $Co^{2+}$  ions on the structure and exchangeinteractions were investigated. The increaseing behavior of inter-ionic distances between cations and variations of bond angles have confirmed that  $In^{3+}$  substituion resulted in the weakening of exchange interaction while beside theoretical predictions in case of cobalt substituion magneto-crystalline anisotropy was responsible to strenghten the exchange interactions.

#### Acknowledgements

One of the authors (Gagan Kumar) is thankful to Mr. Anurag Katiyar (National Physical Laboratory, New Delhi, India) for his constant support during this work. The author (Arun Kumar) is thankful to University Grant Commission, New Delhi (India), for providing research fellowship under the letter.no F. 7-274/2009 (BSR). Conceived the plan: B. S. Chauhan; Performed the expeirments: Gagan Kumar, Virender Pratap Singh, Arun Kumar, Jyoti Shah, Shalendra Kumar; Data analysis: Gagan Kumar, R. K. Kotnala, M. Singh; Wrote the paper. Authors have no competing financial interests.

#### Reference

- Hashim, M.; Alimuddin; Kumar, S.; Ali, S.; Koo, B. H.; Chung, H.; Kumar, R. J. Alloys Compds. 2012, 511, 107. DOI: <u>10.1016/j.jallcom.2011.08.096</u>
- Mansour, S. F.; Elkestawy, M. A. Ceram. Inter. 2010, 37, 1175. DOI: 10.1016/j.ceramint.2010.11.038
- Najmoddin, N.; Beitollahi, A.; Kavas, H.; Mohseni, S. M.; Rezaie, H.; Akerman, J.; Toprak, M. S.; *Ceram. Inter.* 2014, 40, 3619. DOI: <u>10.1016/j.ceramint.2013.09.063</u>
- 4. Singh, Virender Pratap.; Kumar, Gagan.; Dhiman, P. Kotnala, R. K. Shah, Jyoti; Batoo, Khalid. M.; Singh, M. *Adv. Mater. Lett.* **2014**, *5*, 447.
- DOI: <u>10.5185/amlett.2014.554</u>
  5. Raghasudha, M.; Ravinder, D.; Veerasomaiah, P.; *J. Magn. Magn. Mater.* 2014, *355*, 210.
  - **DOI:** <u>10.1016/j.jmmm.2013.12.020</u>
- Venkataraju, C.; Sathishkumar, G.; Sivakumar, K.; J. Magn. Magn. Mater. 2010, 322, 230.
   DOI: 10.1016/j.jmmm.2009.08.043
- Pradeep, A.; Priyadharsini, P.; Chandrasekaran, G.; J. Magn. Magn. Mater. 2008, 320, 2774.
   DOI: <u>10.1016/j.jmmm.2008.06.012</u>
- Tartaj, P.; Morales, M. P.; S. Verdaguer, V.; Gonzalez-Carreno, T.; Serna, C. J. J. Phys. D: Appl. Phys. 2003, 36, R182. DOI: 10.1088/0022-3727/36/13/202
- Lakshman, A.; Rao, K. H.; Mendiratta, R. G.; J. Magn. Magn. Mater. 2002, 250, 92.

DOI: <u>10.1016/S0304-8853(02)00359-1</u>

- Kumar, Gagan; Rani, Ritu; Singh, V.; Sharma, S.; Batoo, K. M.; Singh, M. Adv. Mater. Lett. 2013, 4, 682.
   DOI: <u>10.5185/amlett.2013.1409</u>
- Lakhani, V. K.; Pathak, T. K.; Vasoya, N. H.; Modi, K. B. Solid State Sci. 2011, 13, 539.
- DOI: <u>10.1016/j.solidstatesciences.2010.12.023</u>
- Kumar, Gagan; Chand, J.; Verma, S.; Singh, M.; J. Phys. D. Appl. Phys. 2009, 42, 155001.
   DOI: 10.1088/0022-3727/42/15/155001
- Kumar, Gagan; Chand, J.; Dogra, Anjana; Kotnala, R. K.; Singh, M. J. Phys. Chem. Solids 2010, 71, 375.
   DOI: <u>10.1016/j.jpcs.2010.01.003</u>
- Kumar, Gagan; Kanthwal, M.; Chauhan, B. S.; Singh. M. Ind. J. Pure and Appl. Phys. 2006, 44, 930.
- Kumar, Gagan; Shah, J.; Kotnala, R. K.; Dhiman, P.; Rani, Ritu; Singh, Virender Pratap; Garg, Godawari; Shirsath, Sagar E.; Batoo, Khalid M.; Singh, M. *Ceram. Inter.* **2014**, *40*, 14509.
   **DOI:** <u>10.1016/j.ceramint.2014.07.017</u>
- Chauhan, B. S.; Kumar, Ravi; Jadhav, K. M.; Singh, M. J. Magn. Magn. Mater. 2005, 283, 71.
- DOI: <u>10.1016/j.jmmm.2004.04.133</u>
  17. Shirsath, Sagar E.; Toksha, B. G.; Jadhav, K. M.; *Mater. Chem. Phys.* **2009**, *117*, 163.
- DOI: <u>10.1016/j.matchemphys.2009.05.027</u>
  18. Siokafus, K. E.; Wills, J. M.; Grimes, N. W.; *J. Am. Ceram. Soc.* **1999**, 82, 3279.
  - **DOI:** 10.1111/j.1151-2916.1999.tb02241.x
- Jadhav, S. S.; Shirsath, Sagar E.; Patange, S. M.; Jadhav, K. M. J. Appl. Phys. 2010, 108, 093920.
   DOI: 10.1063/1.3499346
- Vasoya, N. H.; Lakhani, V.; Sharma, P. U.; Modi, K. B.; Kumar, R.; Joshi, H. H. J. Phys.: Condens. Matter. 2006, 18, 8063.
   DOI: 10.1088/0953-8984/18/34/017
- Shirsath, Sagar. E.; Kadam, R. H.; Patange, S. M.; Mane, M. L.; Ghasemi, A.; Morisako, A. *Appl. Phys. Lett.* **2012**, *100*, 042407. DOI: <u>10.1063/1.3679688</u>

#### Advanced Materials Letters

Copyright© VBRI Press AB, Sweden www.vbripress.com

Publish your article in this journal

Advanced Materials Letters is an official international journal of International Association of Advanced Materials (IAAM, <u>www.iaamonine.org</u>) published by VBRI Press AB, Sweden monthly. The journal is intended to provide topquality peer-review articles in the fascinating field of materials science and technology particularly in the area of structure, systnthesis and processing, characterisation, advanced-sate properties, and application of materials. All published articles are indexed in various databases and are available electronic and has fast and fair peer-review process. The journal includes review article, research article, notes, letter to editor and short communications.



JOURNAL