A Review of Doped Magnesium Ferrite Nanoparticles: Introduction, Synthesis Techniques and Applications

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ABSTRACT

Nanosized spinel ferrites have been attracting considerable attention of researchers for their exciting structural, magnetic and electrical properties. The physical and chemical properties of nanomaterials have been enhanced due to their high surface to volume ratio. The curie temperature, magnetic moment, electrical resistivity and lattice constants are found to be affected by substitution in the spinel lattice and nanoparticle sizes. The present paper describes various synthesis techniques used by researchers to prepare doped (Li, Zn, Ca, Cd, Cr, Ce, Mn, Al) magnesium ferrite nanoparticles and their characteristics. Li substituted magnesium ferrite has the ability to create oxygen vacancies and dissociate water molecule on octahedrally coordinated unsaturated surface cations. With increase in Zn concentration in magnesium ferrite, the transition from ferrimagnetic to super paramagnetic is observed. It was observed that the Curie temperature was decreased with increase in Ca concentration in the ferrite. In $Cd_xMg_{1-x}Fe_{2-y}Cr_yO_4$ ferrite, lattice constant was found to be decreasing with increase in Cr^{3+} concentration and increasing with increase in Cd^{2+} concentration. With Ce substitution, magnetic properties were changed. M_s was found first decreasing with increase in Ce^{3+} content and then increasing. With increase in Mn and decrease in Al content in magnesium ferrite, M_s and squareness ration (M_r / M_s) increases.

Keywords : Nanoparticles, Magnesium Ferrite, Substitution, Doping.

I. INTRODUCTION

Spinel ferrites with general formula AB_2O_4, A is divalent transition element and B is Fe have been excellent materials because of their structure, electrical and magnetic properties. These ferrites have large surface to volume ratio and broken exchange bonds which cause spin disorder and make spinning glass like structure lowering the coordination of the atoms on surface producing highly anisotropic surface layer [1, 2]. These disorders affect the properties of affect the properties of ferrites and create difference in cation distribution at surface and non surface atoms due to super exchange interaction through oxygen ions [3, 4]. These ferrites have multifunctional features and have a number of applications in transducers actuators, computer parts, microwave, switching mode power supplies, sensors, information storage devices, gas and humidity sensors etc [5- 9]. The effect of substitution of various elements in nanoferrites is being investigated by many researchers.

II. METHODS AND MATERIAL

Methods of Synthesis of Spinel Ferrites

Method of synthesis play crucial role in controlling the size, uniformity and surface area of materials. Various methods of synthesis of ferrites like microemulsion, ultrasonic (sonochemical), solvothermal, microwave assisted, sol-gel, combustion, ball milling, solid state reaction, hydrothermal and coprecipitation method [10-19] are being used by the researchers. Most commonly used methods are discussed in following subsections.

Ball Milling

Ball milling is widely used for silicate products, cement, building materials, chemical fertilizers, glass, fireproof materials, ceramics etc. Materials can be ground by ball milling in wet or dry form [19]. By this method the materials can be prepared of desired size and large surface area [20].

Sol-Gel

In sol gel method, gel is formed that provides a high degree of homogeneity reducing the requirement for atomic diffusion during solid state reaction. Precursors are mixed together to form a solution and is converted in to a homogeneous oxide (gel) by hydrolysis and condensation. Gel is dried and calcined to get oxide product. To prepare multi component oxides, alcohol is mixed with alkoxides. Process of hydrolysis is carried out under controlled conditions of pH, temperature, amount of water, concentration of alkoxides and alcohol. This technique is low cost and low temperature technique which has fine control on chemical composition of the products [21-24]. Materials derived from these techniques have applications in electronics, optics, space, energy etc.

Co-precipitation Method

In this method, a multi component liquid solution of inorganic salts is combined with a liquid solution of a precipitating substance. This method requires careful monitoring of pH in order to achieve high quality ferrites [25, 26]. The precipitating agent is selected in such a way that one of its radicals combines with the metal ions to form insoluble salts when dissolved with the metal salts. The entire process involves simultaneous growth, nucleation and agglomeration. When the ionic radius and charge of the impurity are similar to those of carrier, the impurity occupies a lattice site in the structure leading to crystallographic defect. Impurity that is weakly bound to the surface of the precipitate is called an adsorbate and when an adsorbed impurity is physically trapped inside the growing crystal an occlusion is said to be occurred.

Solid State Reaction Method

This method is the most widely used. In this method raw materials are mixed with both dry and wet processes. In wet mixing process an aqueous suspension, vibration drum or agitator mill is used. It is extremely effective method but requires heat for drying and dewatering. Raw materials are mixed either by grinding in a drum or a ball mill.

Microemulsion Method

In this method dispersion of two immiscible liquids is done thermodynamically and stabilized by adding surfactant molecules. The particle size can be controlled by changing the surfactants and co-surfactants ratio as well as water to oil ratio [27, 28]. This is low temperature synthesis and eco-friendly method. Main disadvantage of this method is poor crystalline nature of synthesized ferrites, polydispersion due to slow nucleation at low temperature and requirement of large amount of solvents.

Solvothermal Method

For good control on particle size distribution and morphology, the solvothermal method is an eco-friendly method which employs the use of aqueous or non aqueous solvents. By adjusting the experimental conditions such as temperature solvent, time, precursors and surfactants, the size, shape and morphology of ferrites can be altered. This is a simple process and commercial production of ferrites is feasible with enhanced chemical and physical properties [29-31].

Ultrasonic (Sonochemical) Method

The sonochemical method is widely used nowadays due to facile control on synthesis conditions. Homogeneous mixing and control on particle size is achieved by this method. The intensity of ultrasonic waves and temperature affect directly the particle size of ferrites prepared. In this method, bubbles are formed in the reaction medium and ferrites undergo situ calcinations due to induced energy by irradiation of ultrasonic waves [32]. Mixing at atomic level is is achieved by ultrasonification so that the crystalline phase formation is possible by annealing at low temperatures [33].

Microwave Assisted Method

This method is a new technique which ii emerging rapidly for the synthesis of ferrites. Various advantages of this method are simple, fast, high energy efficiency, lower reaction time, good yield and cost effective [24]. In this method heating energy used is internal i.e. microwave energy. Microwave energy is converted to thermal energy and the temperature ranges from 100 to 200 °C.

Li substitution in Magnesium Ferrite

Polycrystalline spinel ferrites series $Li_xMg_{0.5}Ni_{0.5-2x}Fe_{2+x}O_4$ (x=0.00 to 0.25 in steps of 0.05) was synthesized by double sintering method sintered in air at 1200 °C by M.K. Das et al in 2013. Curie temperature and the real part of the complex initial permeability of the prepared ferrite increase with increase in Li content and decrease in Ni content [34]. Lithium substituted magnesium ferrite was prepared by solid state reaction method. Lithium ions occupy octahedral sites causing octahedral sites most oxygen deficient and dissociation of water molecules on octahedral coordinated unsaturated surface cations. These properties of lithium substituted magnesium ferrite are used in the applications of humidity sensor and hydroelectric cell [35]. Lattice parameter, molecular mass, theoretical density, bulk density porosity and Curie temperature of $Li_xMg_{0.5}Ni_{0.5-2x}Fe_{2+x}O_4$ are presented in table I and II.

Table I. Lattice parameter, molecular mass, theoretical density, bulk density and Porosity of $Li_xMg_{0.5}Ni_{0.5-2x}Fe_{2+x}O_4$

Ni content x	Molecular mass, M	Sintering temperature, T_s	Lattice parameter a (Å)	Theoretical Density g/cc	Bulk density g/cc	Porosity %
0.0	237.135	1200 °C	8.366	4.924	4.206	14.58
0.10	228.870		8.368	4.982	4.307	13.55
0.15	226.140		8.433	5.008	4.404	12.06
0.20	222.160		8.435	5.024	4.434	11.74
0.25	220.680		8.438	5.051	4.469	11.52

Composition	X	T_c
$Li_xMg_{0.5}Ni_{0.5-2x}Fe_{2+x}O_4$	0.00	528
	0.10	532
	0.15	545
$Li_xMg_{0.5}Fe_{2+x}O_4$	0.25	547

From the above table I, it is observed that with increase in value of x concentration of Li increases while concentration of Ni decreases causing increase in lattice parameter, bulk density and porosity. From table II, we find that Curie temperature increases with increase in Li concentration.

Zinc Substituted Magnesium Ferrite

Zinc substituted magnesium ferrite $Mg_{1-x}Zn_xFe_2O_4$ (x=0, 0.1, 0.3, 0.5, 0.7) was prepared by sol gel auto combustion method by Yun He et al in 2015. Thorough analysis it was found that lattice parameter increases and average crystallite size decreases with increase in Zn concentration. Particles are agglomerated due to the presence of magnetic interactions among the particles. Lattice parameter, average crystallite size, density, Mössbauer parameters of isomer shift (IS), quadrupole splitting (QS), magnetic hyperfine field (H), line width (Γ) and absorption area (A) for $Mg_{1-x}Zn_xFe_2O_4$ are shown in tables III and IV.

Table III. Lattice parameters, average crystallite size and X-ray densities of $Mg_{1-x}Zn_xFe_2O_4$ annealed at 800 °C

Sample (x)	Lattice parameter (Å)	Average crystallite size (Å)	Density g/cc
0	8.39786	411	4.4859
0.1	8.39491	356	4.5829
0.3	8.40864	322	4.7440
0.5	8.43133	377	4.8879
0.7	8.43576	385	5.0620

Table IV. Mössbauer parameters of isomer shift (IS), quadrupole splitting (QS), magnetic hyperfine field (H), line width (Γ) and absorption area (A) for $Mg_{1-x}Zn_xFe_2O_4$

Sample (x)	Component	IS (mm/s)	QS (mm/s)	H (T)	Γ (mm/s)	A_o (mm/s)
0	Sextet (A)	0.163	0.011	45.871	0.503	17
	Sextet (B)	0.332	0.032	43.306	0.325	83
0.1	Sextet (A)	0.224	0.077	45.059	0.473	15
	Sextet (B)	0.294	-0.028	41.322	0.313	85
0.3	Sextet (B)	0.291	-0.009	34.072	0.363	100
0.5	Sextet (B)	0.318	0.005	24.234	0.268	100
0.7	Double	0.336	0.472	-----	0.357	100

From table III and IV, Mössbauer spectra of $Mg_{1-x}Zn_xFe_2O_4$ at room temperature shows that with increase in Zn concentration A- Mössbauer absorption area decreases and B- Mössbauer absorption area increases. Transition from ferromagnetic to super paramagnetic behavior is seen with increase in zinc concentration by Mössbauer spectra at room temperature can be explained with Neel's theory. It was found that the saturation magnetization increases and coercivity decreases with increase in zinc content [36].

A. M. Gismelseed et al in 2014 prepared zinc magnesium ferrite chromate $Mg_{1-x}Zn_xFeCrO_4$ ($0.0 \leq x \leq 1.0$) by solid state double sintering ceramic technique.

Table V. Mössbauer hyperfine parameters at 78 K, and the lattice constants of $Mg_{1-x}Zn_xFeCrO_4$

Paramagnetic doublet				Magnetic hyperfine distribution			
X	δ	ΔE_Q	A(%)	δ	$(B_{hf})_{Aver}$	A(%)	Lattice constant (Å)
0.0	----	----	---	0.41	45.4	100	8.3558
0.2	0.42	0.46	39	0.41	33.7	61	8.3561
0.4	0.41	0.47	48	0.42	25.1	52	8.3682
0.6	0.42	0.48	55	0.43	20.5	45	8.3763
0.8	0.43	0.48	78	0.43	12.9	22	8.3807
1.0	0.43	0.50	100	----	----	----	8.3835

From table V, X-Ray analysis reveals that the lattice parameter increases linearly with increase in zinc content. Due to incomplete magnetic ordering caused by random environments around the Fe nuclei the magnetic broadening for Zn > 0.0 takes place. Gradual transformation from partial inverse to normal spinel structure is observed due to gradual increase of the zinc content in $Mg_{1-x}Zn_xFeCrO_4$ [37].

Calcium Substituted Magnesium Ferrite

By solid state reaction route pure and calcium substituted magnesium ferrite $MgCa_xFe_{2-x}O_4$ (x= 0.00, 0.03, 0.05, 0.07) were synthesized successfully by K.K. Bamzai et al in 2014. Various parameters like size, composition, lattice parameter, X-ray density, bulk density, porosity and magnetic properties are presented in tables VI to IX below.

Table VI. Variation of grain size with different composition of Ca in $MgCa_xFe_{2-x}O_4$ (x= 0.00, 0.03, 0.05, 0.07)

Composition	Size (μm)
Pre MgF	3.99
Ca 1%	3.26
Ca 3%	2.37
Ca 5%	1.67
Ca 7%	1.30

Table VII. Experimental values obtained from the spectrum of energy dispersive X-ray analysis for various constituent elements present in magnesium ferrite.

Element	MgFe (pure)		MgFe (Ca 1%)		MgFe (Ca 3%)		MgFe (Ca 5%)		MgFe (Ca 7%)	
	At %	Wt %	At %	Wt %	At %	Wt %	At %	Wt %	At %	Wt %
O	57.65	31.49	58.39	31.94	60.13	34.33	56.43	31.35	56.66	33.11
Mg	10.93	9.07	10.16	8.44	10.09	9.03	11.54	9.74	13.77	12.23
Fe	30.93	58.98	30.62	58.47	25.0	49.82	26.20	50.80	19.73	40.20
Ca	----	----	0.84	1.15	4.77	6.82	5.83	8.12	9.84	14.41

Table VIII. Lattice parameter "a", X-ray density "D_x", bulk density "D_B", and porosity "P", for different composition

Composition	Lattice parameter "a" (Å)	X-ray density "D_X" (g/cc)	Bulk density "D_B" (g/cc)	Porosity "P" (%)
Pure MgF	8.3848	4.5062	3.864	15
Ca 1%	8.4108	4.4610	3.598	19
Ca 3%	8.4405	4.4071	3.225	26
Ca 5%	8.4211	4.4783	3.692	17
Ca 7%	8.4046	4.4721	4.061	9

Table IX. The values of saturation magnetization (M_s), coercivity (H_c), residual magnetization (M_r), and Curie temperature (T_c) for pure and substituted MgF

Number of Ca atoms substituted	Saturation magnetization "M_s" (emu/g)	Coercivity "H_c" (Oer)	Residual magnetization "M_r" (emu/g)	Curie temperature "T_c" (°C)
0.00	23.5	26	1.52	400
0.01	22.5	28	1.53	388
0.03	24.5	31	2.00	370
0.05	30.7	20.5	1.38	331
0.07	29.0	30	1.96	325

XRD analysis reveals that the lattice parameter increases up to x ≤ 0.03 and then decreases for x > 0.03. The magnetization increases up to x ≤ 0.05 and then decreases for x > 0.05 cation distribution is created by the replacement of iron and calcium ions according to the given formulae $(Ca_x^{2+}Mg_y^{2+}Fe_{1-x-y}^{3+})^A$ $[Mg_{1-x-y}^{2+} Fe_{1+x+y}^{3+}]^B$ O_4^{2-} and $(Ca_{x-y}^{2+}Fe_{1+y-x})^A$ $[Mg_{1-x}^{2+}Ca_y^{2+}Fe_{1+x-y}^{3+}]^B$ O_4^{2-}. Curie temperature is highest for $MgFe_2O_4$ which decreases with increase in substitution of Ca^{2+} ions. This is due to the pre sence of Mg^{2+} and Ca^{2+} ions on A- sites or on B-sites causing a decrease in Fe_A^{3+} - Fe_B^{3+} magnetic interactions [38].

Cd²⁺ and Cr³⁺ Substituted Magnesium Ferrite

S.A. Masti et al in 2014 synthesized spinel ferrite series $Cd_xMg_{1-x}Fe_{2-y}Cr_yO_4$ with x = 0, 0.2, 0.4, 0.6, 0.8 and 1.0; y = 0, 0.05 and 0.1 by double sintering ceramic method. Structural parameters, Wave number and force constant of $Cd_xMg_{1-x}Fe_{2-y}Cr_yO_4$ are illustrated in tables X and XI.

Table X. Structural parameters of $Cd_xMg_{1-x}Cr_yO_4$ ferrites system

x	y	Lattice constant "a" (Å)	Ionic radii "r_A" (Å)	Ionic radii "r_B" (Å)	Bond Length A-O (Å)	Bond length B-O (Å)	X-ray density d_x g/cc
0.0	0.00	8.36	0.58	0.71	1.91	2.03	4.53
0.2		8.43	0.62	0.72	1.94	2.04	4.81
0.4		8.50	0.65	0.72	1.97	2.04	5.08
0.6		8.57	0.68	0.73	2.00	2.05	5.33
0.8		8.63	0.72	0.73	2.04	2.05	5.58
1.0		8.70	0.77	0.73	2.09	2.05	5.80
0.0	0.05	8.35	0.59	0.71	1.91	2.03	4.50
0.2		8.42	0.62	0.71	1.94	2.03	4.80
0.4		8.48	0.65	0.72	1.96	2.04	5.05
0.6		8.54	0.67	0.72	1.99	2.05	5.32
0.8		8.60	0.72	0.72	2.41	2.04	5.33
1.0		8.66	0.76	0.73	2.08	2.04	5.80
0.0	0.10	8.34	0.58	0.70	1.90	2.02	4.47
0.2		8.40	0.61	0.71	1.93	2.03	4.78
0.4		8.46	0.65	0.71	1.97	2.03	5.04
0.6		8.52	0.65	0.72	1.97	2.04	5.34
0.8		8.58	0.71	0.72	2.03	2.04	5.47
1.0		8.64	0.76	0.73	2.08	2.04	5.70

Table XI. Wave number and force constant of $Cd_xMg_{1-x}Fe_{2-y}Cr_yO_4$

Composition		Frequency of vibrations cm^{-1}		Force constants dyne/cm	
x	y	ν_1	ν_2	K_T	K_O
0.0	0.00	571	434	249880	118670
0.2		575	472	256528	125398
0.4		550	471	265079	124616
0.6		563	466	247099	118687
0.8		556	451	230809	107879
1.0		540	441	230809	105852

0.0	0.05	541	434	267160	118671
0.2		540	431	245313	124305
0.4		581	470	255312	124317
0.6		568	465	241916	120102
0.8		559	437	237581	108891
1.0		550	457	238760	111010
0.0	0.10	623	423	279871	104042
0.2		604	425	279871	107042
0.4		590	471	265989	124643
0.6		586	467	265070	118712
0.8		574	456	255125	110103
1.0		559	439	237553	119801

Through XRD analysis it was found that the lattice constant increases with Cd^{2+} concentration and decreases with Cr^{3+} concentration which is due to the difference of ionic radii Cd^{2+}, Cr^{3+} and Fe^{3+} ions. With increase in Cd^{2+} content A-O and r_A increase while B-O and r_B found to decrease with substitution Cr^{3+} ion which implies that Cr^{3+} occupy B-sites. The force constant K_T decreases while K_O increases with Cd^{2+} substitution. With increase in concentration of Cr^{3+} the force constant K_O increases [39].

Effect of Cerium substitution in Nanocrystalline Magnesium Ferrite

Syed Ismail Ahmad et al in 2016 synthesized nanocrystalline magnesium ferrite $MgCe_xFe_{2-x}O_4$ (x = 0.00, 0.02, 0.04 and 0.06) by sol-gel auto combustion process and the effect of cerium substitution in this ferrite has been studied. Cation distribution, band position, force constant, Lattice constants, atomic radii, bond length, hopping lengths, Saturation magnetization, coercivity, remanance, squareness and magnetic moment for formula unit for experimental and theoretical and Y-K angle of Ce- substituted MgF, $MgCe_xFe_{2-x}O_4$ at different concentration of ceria are shown in tables XII to XIV below.

Table 12. Cation distribution, band position and force constant at tetrahedral and octahedral positions

xCe	Chemical formula	A-site	B-site	v_1 (cm^{-1})	v_2 (cm^{-1})	F_A ×10^5 (dyne/cm)	F_B×10^5 (dyne/cm)
0.00	$MgFe_2O_4$	$Mg_{0.1}Fe_{0.9}$	$Mg_{0.9}Fe_{1.1}$	572.87	426.28	2.4049	1.3316
0.02	$MgCe_{0.02}Fe_{1.98}O_4$	$Mg_{0.08}Fe_{0.92}$	$Mg_{0.92}Fe_{1.08}$	572.87	430.10	2.4049	1.3555
0.04	$MgCe_{0.04}Fe_{1.96}O_4$	$Mg_{0.06}Fe_{0.94}$	$Mg_{0.94}Fe_{1.06}$	565.16	430.23	2.3406	1.3536
0.06	$MgCe_{0.06}Fe_{1.94}O_4$	$Mg_{0.04}Fe_{0.96}$	$Mg_{0.96}Fe_{1.04}$	559.37	432.06	2.2928	1.3679

Table 13. Lattice constants, atomic radii, bond length and hopping lengths at A and B sites

MgCe$_x$Fe$_{2-x}$O$_4$	A$_{exp}$ (Å)	r$_A$ (Å)	r$_B$ (Å)	ath	D (nm)	A-O (Å)	B-O (Å)	L$_A$ (Å)	L$_B$ (Å)
x = 0.00	8.351	0.6731	0.6835	8.4109	45.26	1.8937	2.0606	3.6419	2.9732
x = 0.02	8.352	0.6724	0.6934	8.4364	42.42	1.8990	2.0669	3.6529	2.9822
x = 0.04	8.355	0.6718	0.7033	8.4618	42.82	1.9047	2.0731	3.6639	2.9912
x = 0.06	8.357	0.6712	0.7132	8.4873	46.47	1.9104	2.0793	3.6750	3.0001

Table 14. Saturation magnetization, coercivity, remanance, squareness and magnetic moment for formula unit for experimental and theoretical and Y-K angle of Ce- substituted MgF, MgCe$_x$Fe$_{2-x}$O$_4$ at different concentration of ceria.

xCe	M$_s$ (emu/g)	H$_c$ (G)	M$_r$ (emu/G)	R^2 = M$_r$M$_s$	ηB$_{exp}$ (μ$_B$)	ηBx (μ$_B$)	α$_{Y-K}$
0.00	13.59	120	2.08	0.153	0.480	1	27.9
0.02	7.40	66.97	0.39	0.053	0.267	0.8	28.52
0.04	9.65	95.26	1.11	0.115	0.3516	0.6	19.56
0.06	17.42	112.33	2.61	0.150	0.6394	0.4	18.95

Single phase cubic spinel structure and increase in lattice parameter with increase in cerium concentration are revealed by X-Ray Diffraction. Cerium substitution leads to act as grain growth inhibitor. In FTIR spectra the presence and shifting of two bands v_1 and v_2 towards higher and lower frequencies reveals the presence of Ce^{3+} ions with Fe^{3+} ions at octahedral sites. Due to the formation of Ce^{3+}-O^{2-} complex at B-sites bond length is increased. Fe^{3+} ions migrate from A-site to B-site because of the depletion of Mg^{2+} ion and the presence of the large concentration of Ce^{3+} ions causing increase in saturation magnetization. These ferrites can be used in catalytic activities and humidity sensing [40].

Mn and Al doped Magnesium Ferrite

Ming-Feng Kuo et al in 2016 prepared spinel ferrites (Mg$_{1.3-x}$Mn$_x$Al$_y$Fe$_{1.8-y}$O$_4$, x = 0.1-0.2, y = 0.15-0.3) by conventional ceramic technique. The influence of Mn and Al substitution on various properties of these ferrites has been studied. Calculated lattice constant, theoretical density, sintered density, magnetic properties, initial permeability and Curie temperature of Mg$_{1.3-x}$Mn$_x$Al$_y$Fe$_{1.8-y}$O$_4$ ferrites are shown in tables XV to XVII below.

Table 15. Calculated lattice constant, theoretical density and sintered density of $Mg_{1.3-x}Mn_xAl_yFe_{1.8-y}O_4$ ferrites

Sample	Lattice constant (Å)	Theoretical density (g/cc)	Sintered density (g/cc)
$Mg_{1.20}Mn_{0.10}Al_{0.30}Fe_{1.50}O_4$	8.34	4.27	4.24
$Mg_{1.16}Mn_{0.14}Al_{0.25}Fe_{1.55}O_4$	8.35	4.31	4.30
$Mg_{1.13}Mn_{0.17}Al_{0.20}Fe_{1.60}O_4$	8.36	4.38	4.34
$Mg_{1.10}Mn_{0.20}Al_{0.15}Fe_{1.65}O_4$	8.36	4.44	4.38

Table 16. Magnetic properties of $Mg_{1.3-x}Mn_xAl_yFe_{1.8-y}O_4$ ferrites

Sample	$4\pi M_s$ (G)	B_r (G)	H_c (Oe)	SQR	ΔH (Oe)
$Mg_{1.20}Mn_{0.10}Al_{0.30}Fe_{1.50}O_4$	958	750	1.55	0.78	214.3
$Mg_{1.16}Mn_{0.14}Al_{0.25}Fe_{1.55}O_4$	1110	951	1.61	0.86	182.8
$Mg_{1.13}Mn_{0.17}Al_{0.20}Fe_{1.60}O_4$	1349	1201	1.48	0.89	143.8
$Mg_{1.10}Mn_{0.20}Al_{0.15}Fe_{1.65}O_4$	1521	1396	1.36	0.92	192.0

Table 17. Initial permeability and Curie temperature of $Mg_{1.3-x}Mn_xAl_yFe_{1.8-y}O_4$ ferrites

Sample	L (μH)	Q	μ@100kHz	T_c (°C)
$Mg_{1.20}Mn_{0.10}Al_{0.30}Fe_{1.50}O_4$	1.75	6.82	56	180
$Mg_{1.16}Mn_{0.14}Al_{0.25}Fe_{1.55}O_4$	2.18	8.29	75	200
$Mg_{1.13}Mn_{0.17}Al_{0.20}Fe_{1.60}O_4$	1.45	4.83	51	220
$Mg_{1.10}Mn_{0.20}Al_{0.15}Fe_{1.65}O_4$	1.45	5.50	46	240

The results show that the value of $4\pi M_s$ in samples increases with decrease in substitution of Al and the squareness ratio increases with increase in substitution of Mn. When x was greater than 0.17 in $Mg_{1.3-x}Mn_xAl_yFe_{1.8-y}O_4$ the SQR could reach 0.9. By adjusting the content of Al, the value of $4\pi M_s$ of sample C was obtained to be 1349 G which is suitable for a 10 GHz working frequency. The resonance line width was smallest while Curie temperature was 220 °C for sample C which is high enough for microwave application devices with general power [41].

Table 18. Effect of Substitution on Various Characteristics of Magnesium Ferrite

	Substitution/ Doping							
Characteristics	Li	Zn	Ca	Cd	Cr	Ce	Mn	Al
Lattice Parameter		Increases	Increases then Decreases	Increases	Decreases	Increases		
Particle Size								
Curie Temperature	Increases		Decreases					
Saturation Magnetization			Increases then Decreases				Increases	Increases	Decreases
Retentivity								
SQR							Increases	

III. RESULTS AND DISCUSSION

Applications

Spinel ferrites have a large number of applications including high frequency component, biomedical, low temperature co-fired ceramic (LTCC) devices, sensors and biosensors, microwave absorption, photocatalytic activity and supercapacitors.

High Frequency Components

Spinel ferrites (MFe_2O_4, M = Mg, Co, Mn etc) are used in various applications such as communications, computers, remote monitoring, household appliances, transformers, transducers etc [42]. Ferrite based magnetic materials are highly required in electronic industries due to arrival of high-frequency applications because the regular techniques of reducing eddy currents have become less effective using iron cores.

Biomedical

Magnetic naoparticles are used in various biomedical applications like magnetic resonance imaging (MRI), cell separation, magnetic carriers in bio-screening, contrast enhancement, cell separation, cancer treatment, tissue repair, hyperthermia etc [43]. In magnetic hyperthermia technique, spherically shaped ferrite nanoparticles can selectively kill cancer cells by by raising their temperature in the range 41-46 °C [44].

LTCC Devices

LTCC materials have gained a lot of importance due to their small size and mass by the advent of miniaturization of electronic appliances. M-type barium ferrite and NiCuZn are widely used to manufacture components in miniature form of transformers, capacitors, microwave gyromagnetic devices and components of video cameras, cell phones, laptops etc. These ferrites are used as wire wound chip inductor and multilayer chip inductor [45-47].

Sensors and Biosensors

Various ferrite nanoparticles are widely used as sensors for detection of different analytes.

Samarium (Sm) doped cobalt ferrite is used for hydrogen leakage [48] and Co-Mn ferrite is used for application as CO_2 sensor [49]. Ferrites are also good materials for electrochemical biosensor because of their high sensing accuracy, quick analysis time and low detection level of analyte [50].

Microwave Absorption

Today, with the advancement of technology a number of applications like cell phones, satellite communications, radio broadcasting, wireless networks and GPS operate at microwave frequency range (1 – 18 GHz) [51]. Working of these systems can be affected severely by unwanted emissions or reflections along with health risks. Ferrites play an important role in damping, suppression or reflection of electromagnetic waves. Some of the best absorbing ferrites in microwave frequency range are doped barium ferrite, $SrFe_{12}O_{19}/TiO_2$, Li-Zn ferrite doped with Mg and La, Ce substituted barium ferrite, Ni and Zn substituted Sr ferrite and $MnFe_2O_4$/wax [52-56].

Photocatalytic Activity

Ferrites have the characteristics of absorbing visible light with band gap in the range 1.1 - 2.3 eV and are promising photocatalysts. Due to spinel structure of metal ferrites extra catalytic reaction sites result in increased photocatalytic degradation efficiency. Being magnetic substances ferrites can easily be separated. Ferrites are used as photocatalysts for a number of industrial processes including photo-phenton like process, oxidative dehydrogenation of hydrocarbons, the treatment of exhaust gases, decomposition of alcohols and hydrogen peroxide, the hydroxylation of phenol and many more [57-59].

Supercapacitors

Many metal ferrites like $SnFe_2O_4$, $CoFe_2O_4$ are being used for charge storage applications. Doped manganese ferrite mounted on grapheme nanosheets showed increased capacitive performancedue to the synergistic effect of electric double layer capacitance and faradic behavior. In various morphologies, the ferrites have influence in varying the surface area of capacitors to different supercapacitive values. More the surface area more is the charge storage capacity [60-62].

IV. CONCLUSION

There are various methods of preparation of magnesium ferrite like double sintering, chemical co-precipitation, sol gel auto combustion, ball milling and solid-state reaction method. Nearly in all the methods particles are found to be agglomerated due to presence of magnetic interactions. The spinel ferrites prepared through ceramic methods have size in micrometer range (10^{-6} m). Homogeneity in particles and low temperature synthesis are the main advantages of chemical co-precipitation and ball milling methods. It is observed that the lattice parameter increases with substitution or doping of Zn, Cd, Ce and decreases due to substitution of Cr. Curie temperature increases with increase in Li content and decreases with increase in Ca substitution in calcium magnesium ferrite. Saturation magnetization increases with increase in Ce and Mn, and decreases with increase in Al concentration.

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