

Synthesis and design of nanostructured $\text{Mg}_{(2-x)}\text{Gd}_x\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ ferrites thin films for high performance EMI Shielding applications

Koushalya P.R

Don Bosco Institute of Technology

Prathibha B. S

Government Srikrishnarajendra Silver Jubilee Technological Institute

Manjunatha S.O

`manjunatha.phy@bmsce.ac.in`

BMS College of Engineering

T. M Gurumurthy

Vijaya College, Affiliated to Dr. Manmohan Singh Bengaluru City University

Latha A.L Pasha

Ghousia College of Engineering

Ravikumar H. C

Dayananda Sagar Academy of Technology and Management

Syed Saleem Pasha

Ghousia College of Engineering

Apsar Pasha

Ghousia College of Engineering

Research Article

Keywords: Spinel ferrites, Solution combustion, MGNA composite films, Dielectric properties, Attenuation and EMI-Shielding

Posted Date: September 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10998354/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Synthesis and design of nanostructured $\text{Mg}_{(2-x)}\text{Gd}_x\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ ferrites thin films for high performance EMI Shielding applications

Koushalya P.R.¹, Prathibha B.S.², Manjunatha.S.O.^{3*}, Gurumurthy T.M.⁴, Latha A.L.⁵, Ravikumar H.C.⁶, Syed Saleem Pasha⁷, Apsar Pasha^{8*}

¹Department of Physics, Don Bosco Institute of Technology, Kumbalagodu, Mysore Road, Bengaluru -560074, Karnataka State, India.

²Department of Physics, Government Srikrishnarajendra Silver Jubilee Technological Institute, Bengaluru-560001, Karnataka State, India.

³Department of Physics, BMS College of Engineering, Bull Temple Road, Bengaluru 560019, Karnataka State, India.

⁴Department of Physics, Vijaya College, Affiliated to Dr. Manmohan Singh Bengaluru City University, 4th Block, Jayanagar, Bangalore-560011, Karnataka State, India.

⁵Department of Physics, Government College for Women (Autonomous), Mandya-571401, Karnataka State, India.

⁶Department of Electronics and Communication Engineering, Dayananda Sagar Academy of Technology and Management, Bengaluru-560082, Karnataka, India.

⁷Department of Robotic and Artificial Intelligence, Ghousia College of Engineering, Ramanagara, Bangalore South District-562159, Karnataka State, India.

⁸Department of Physics, Ghousia College of Engineering, Ramanagara, Bangalore South District-562159, Karnataka State, India.

Corresponding Authors*: Dr. Manjunatha.S.O (email: manjunatha.phy@bmsce.ac.in)
Dr. Apsar Pasha (email: apsarpasha1982@gmail.com)

Abstract:

In the present work, gadolinium (Gd^{3+}) doped magnesium nickel aluminate spinal ferrite ($\text{Mg}_{(2-x)}\text{Gd}_x\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$) thin films (abbreviated as MGNA) were prepared through low-cost solution combustion method and investigated for electromagnetic interference (EMI) shielding applications. Doping of Gd^{3+} rare earth metal nanoparticles (NPs) into $\text{Mg}_{(2-x)}\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ spinal ferrites, the morphology, structure, optical, thermal, and electromagnetic properties are significantly improved. The synthesized MGNA composite thin films are characterized via scanning electron microscopy (SEM), energy dispersive X-ray (EDX), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), UV–visible spectroscopy, and thermogravimetric analysis (TGA) to examine the structure, thermal stability and formation of single phase in the prepared MGNA composite thin films. The average crystallite size through XRD analysis was carried out was found approximately 51 nm dimension. The temperature dependent of electrical conductivity for MGNA ($x=0.75$) composite thin film was found to be 120 S/cm. Doping of Gd^{3+} NPs modifies the structural arrangement and electronic features of MGNA composite thin films, which can greatly influence charge transport, polarization, dielectric loss, and magnetic loss mechanisms. These mechanisms are important to converting electromagnetic radiation into heat and thereby reducing the transmission of unwanted electromagnetic waves. Due to the enhanced dielectric and magnetic characteristics of MGNA ($x=0.75$) composite thin film with thickness about $50\pm 2\ \mu\text{m}$ was displayed the improved absorption dominated EM shielding efficiency in the order of $-26.25\ \text{dB}$, this value approximately 99.89% of shielding efficiency in broad band microwave frequency range (8GHz-18GHz). Furthermore, Gd^{3+} NPs doping in spinal ferrites provides an effective method for tuning the EMI shielding features of MGNA composite thin films. The combination of good structural characteristics, thermal stability, optical properties, and electromagnetic response makes MGNA composite thin films as a promising material for EMI shielding applications and very beneficial for defence and electronic applications.

Keyword: Spinal ferrites, Solution combustion, MGNA composite films, Dielectric properties, Attenuation and EMI-Shielding.

1. Introduction

The fast development in modern communication technology has brought enormous benefits and improved the competence of modern living system. Therefore, the extensive utilisation of modern electronic gadgets has led to rigorous electromagnetic wave pollution in the surrounding atmosphere [1]. Especially, the advancements in digital electronics, internet of things (IoT), wireless communications system, and artificial intelligence (AI) have been a benefit for technological development. Therefore, these discoveries also come with the risks of enhanced electromagnetic pollution [2]. The resultant electromagnetic radiation and its interference not only destroy the working of more accurate electronic devices but also exhibits possible damage to human health. The increase of high-powered electronics, radio sources, and rapid telecommunication equipment has turn to the liberation of electromagnetic (EM) waves that destroy the regular working of other electronic devices, so that EMI shielding is becoming necessary [3]. Subsequently, the more requirement for efficient electromagnetic wave absorbing materials utilised to manage these kinds of common electromagnetic wave risks [4]. These advanced materials work on attenuating the incident EM waves via reflection and absorption mechanisms. The EMI shielding application in particular consist of three types of mechanism where the shielding materials reflect, absorb, and repeated internal reflection of incident electromagnetic waves. The main condition for the shielding process is that materials impedance must be correlated with the free space impedance so that incident EM waves are appropriately attenuated by the shielding material [5-6]. Spinel ferrites composites are utilized for electromagnetic interference (EMI) shielding applications owing to they give a combination of improved magnetic permeability, considerable electrical resistivity, and balanced magnetic and dielectric loss process that easily absorb and attenuate undesirable high-frequency EM radiation. At present past, many researchers and technocrats across the world have been put lot of efforts and consideration to design innovative electromagnetic shielding device which involves the exceptional features like low cost, easy to prepare, lower weight, enhanced corrosion features towards the severe atmosphere, and expectational electromagnetic shielding ability to safe guard the electronic sensitive equipment's [7-8]. Spinal ferrites composites-based EMI shielding materials have pinched additional consideration from the research group rather than ceramics based shielding materials owing to their outstanding features such as less weight, compatibility, electro-chemical stability, mechanical flexibility, and easy to convert thin films. The spinel ferrites NPs are related to the family of magnetic materials drawn more

importance owing to their multiple technological usages, such as transformers, battery microwave devices, gas sensors [9-10]. The basic features of the spinal ferrites largely lean over the preparation method, mixing the different magnetic material dopants, presence of temperature and scattering of cations over the matrix which largely impact over the dielectric and magnetic features [11]. At present, nano sized ferrite material largely examined in order to enhance the practical applications at room temperature. The rare earth (RE) metal dopants like samarium, caesium, lanthanum and gadolinium doped into the spinal ferrites, which effects improvements in the EMI shielding properties by changing the crystal geometry, reducing the energy band gap and boosting the magnetic and dielectric parameters in ferrites composites. This blend permits the spinal ferrites composites to absorb and liberate EM waves more across microwave frequency region [12-13]. Currently magnetic material like iron, nickel, magnesium, cobalt and zinc oxide have been extensively studied as a secondary dopant in majority of spinal ferrites composites employed for superior EMI shielding applications worked at GHz frequencies [14]. The capability of the shielding material largely leans over the types of magnetic dopant utilized to enhance the conductivity and dielectric attributes of the ferrites composite thin films. Among the family of magnetic materials nickel and manganese are displayed excellent EM wave reflection features [15]. The EMI shielding performance of pristine ferrites thin film was low and hide the working performance of the most of the electronic gadgets, therefore, by doping technique into the matrix, the magnetic and electromagnetic shielding performance of the composite thin film can be improved significantly [16].

The recent review on published literature witnessed that fascinating variations in spinel-ferrites are possible with the doping of NPs like Gd^{3+} , to attain the requirement of modern technology in advanced firms. Owing to their multifunctional and practical usages in variable diverse sectors, it is compulsorily to investigate the spinel ferrite composites with specific characteristics that may be attained by employing to design and fabrication and the method of doping of diverse rare-earth metal ions [17].

Recently, Somnath Sahu et al [18] studied the “Effect of rare earth substitution on electromagnetic and microwave absorption properties of nickel-cobalt nano ferrite”. By doping of RE metal NPs into the spinal ferrites, the structure and morphology of the composites are drastically improved in compare to pure ferrites sample. The electric, magnetic and dielectric parameters are significantly improved upon inclusion of RE metal NPs in host ferrites. The

maximum shielding effectiveness nearly (-28.37 dB) was noticed at a broad band frequency of 17.80 GHz of a 2 mm thick ferrites film. In this work, they are drawn the conclusion that small quantity of gadolinium (Gd^{3+}) which leads to the probable mechanism for EM wave absorption.

Isha S. Kapte et al [19] examined the “Microwave assisted cobalt nickel ferrite as exhaust thrust sensor and EMI shield”. In this study, the CNF samples were prepared via ceramic method and maintained with high sintering temperature. The structural and morphological behaviour studied through XRD and SEM analysis. The magnetic permeability with as step of temperature has displayed quasi single domain grain features. The CNF shows a net shielding effectiveness in the order of 55.96 dB, signifying that nearly 99.99% of entering EM waves is successfully decreased by this material. In summary this research group drawn the conclusion that ,the spinel ferrite CNF have superior “electromagnetic shielding in microwave “zone and making it very convenient for military and communication applications.

The above published literature demonstrated that spinal ferrite composites are possess excellent potential for electromagnetic interference (EMI) shielding owing to their superior magnetic, dielectric, and microwave absorption features. However, limited studies have been focused on MGNA thin films, particularly with respect to optimizing their EMI shielding application. These research gaps have motivated us to carry out the present investigation to develop and systematically evaluate MGNA ferrite thin films for EMI shielding applications.

To the best of our knowledge and believes, the selected $Mg_{(2-x)}Gd_xNi_{(1-x)}Al_2O_4$ spinel ferrite composition has not been extensively investigated for electromagnetic interference (EMI) shielding applications. The present study therefore explores its potential as an effective EMI shielding material by systematically correlating its structural, morphological, optical, thermal, electrical, and magnetic properties with its shielding performance.

Herein, we report the MGNA ($x=0.0, 0.25, 0.50$ and 0.75) composite thin films which made up of manganese, gadolinium nickel and aluminate NPs as an excellent EMI shielding for broad band frequency applications. The novel MGNA spinal ferrites composite thin films showed an enhanced conductivity, dielectric, magnetic features and outstanding EMI shielding efficiency in the order 99.89% in the entire broad band microwave frequencies zone. The unique properties of properties displayed by MGNA composites thin films and experimental findings provide new insights into the suitability of this ferrite system for EMI attenuation and highlight its potential for use in next-generation electromagnetic shielding devices.

2. Experimental

2.1 Materials

All materials and chemicals are used in present research work are research grade. Magnesium, Gadolinium, Nickel, Aluminate metal nitrate powder and “N-Methyl-2-pyrrolidone (NMP) (99.50%)” are obtained from Sigma Aldrich (South-India) with pureness about (99.95%). All materials, chemicals and different reagents are utilized as present form to synthesized MGNA composites thin film without any further purification.

2.2 Synthesis of MGNA spinal ferrites

In the current research work we utilized solution combustion method to prepare spinal MGNA ferrites NPs. The solution combustion technique suggested the economical and controlled the surface morphology and structures of spinal ferrites in compare to the other conventional synthesis method. The stoichiometric mass of metal nitrate powders like $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$, $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and act as an oxidising material and equal amount of fuel like “glucose and urea” behave as reducing material. The precursor’s materials are thoroughly mixed in ionized double ultra-pure water and rotated with the help of magnetic stirrer with 200 rpm speed about 60 minutes to achieve well dispersion transparent solution. The well mixed solution was shifted to muffle oven for sintering process and subjected the temperature close to $600 \pm 10^\circ\text{C}$ for sintering mechanism. The chemical solution of well dispersed manganese, gadolinium, nickel and aluminate ferrites metal NPs was baked at optimal temperature, during the sintering mechanism, maximum toxic gases are liberated to ambient atmosphere. The total mass of spinal ferrites NPs was achieved as main yield in the kind of black coloured nano dimension powder was attained. The synthesized black spinal ferrites NPs powder was thoroughly mixed with the help of pestle and agate electric motor. To confirm the formation of single phase in the synthesized spinal MGNA ferrites NPs we have done the XRD analysis.

2.3 Synthesis of MGNA composite thin films

0.3 gram of MGNA spinal ferrite NPs powder mixed with 30 ml N-Methyl-2-pyrrolidone (NMP), to create a saturated solution. The attained aqueous solution was spined about 24 hours. Then the aqueous solution was purified by employed Whatman filter paper of pore dimension of $50\ \mu\text{m}$ to achieve the transparent ferrites solution. Before preparation of thin films, the PET (Polyethylene Terephthalate) base substrate was well cleaned by using isopropyl alcohol (IPA) and then cleaned in double filtered pure water, after this treatment the substrates are shifted to dynamic oven up to a duration of 6 hours. Finally, MGNA composite thin films are removed

from the surface of PET substrate. The prepared MGNA composite thin films are transferred to dynamic oven by keeping a constant temperature of 125°C for annealing process to eliminate the absorbed moisture on the exterior surface of films. Finally, the dimension of the thin film near to $50 \pm 2 \mu\text{m}$ was attained. In order to measure the EMI shielding parameters in the MGNA composite thin films were cut into the dimension of $3.5\text{cm} \times 2\text{cm}$ to fit exactly in sample holder of VNA [20].

2.4 Characterizations

The synthesized MGNA ($x = 0.0, 0.25, 0.50$ and 0.75) composites thin films are characterized by utilized different analytical and spectroscopic techniques to validated the micro structural and morphological characteristics. The exterior surface morphology of prepared MGNA composites thin films are done by employed scanning electron microscope (SEM) (Model: Jeol:6390 LA OXFORD XMX N). The elemental mapping confirmation in the synthesized thin films are done via energy dispersive X-ray spectroscopy (EDX) by employed Bruker QUANTAX 200 analyser. The absorption in the synthesized composites thin films is carried out by employed ultraviolet “visible spectroscopy” (UV-vis) (Model: Perkin Elmer Lambda 365). The creation of mono phase in the synthesized thin films was recorded through using X-ray diffractometer (Model: Bruker D8 Advance) from the range $2\theta = 10^\circ$ to 80° $\text{CuK}\alpha$ ($\lambda = 1.5418\text{\AA}$). The various functional groups present in the MGNA composites thin films are measured via Fourier transform infrared spectroscopy (FTIR) (Thermo Nicolet IS50) from 500cm^{-1} to 4000cm^{-1} stretching frequency region. Thermal degradation behaviour of the composites thin films was recorded via thermo gravimetric analyser (TGA) (Hitachi STA7000). The composites thin films are synthesized by employed spin coating technique (Model no: HO-TH-05). The temperature dependent conductivity of the synthesized composites thin films was measured by utilized four probes technique (Keithley I-V source 2450). The electromagnetic interface (EMI) shielding measurement of the synthesized thin films were performed by utilized “Vector Network Analyser (VNA) (Model: Hewlett Packard-8510 C)” with a microwave frequency region of 50 MHz to 25 GHz. In the current study, the EMI shielding measurements are done in the X-band microwave frequency range of 8GHz to 18GHz by used waveguide model WR90. The flow chart of preparation of MGNA composite thin films are illustrated in the Figure.1

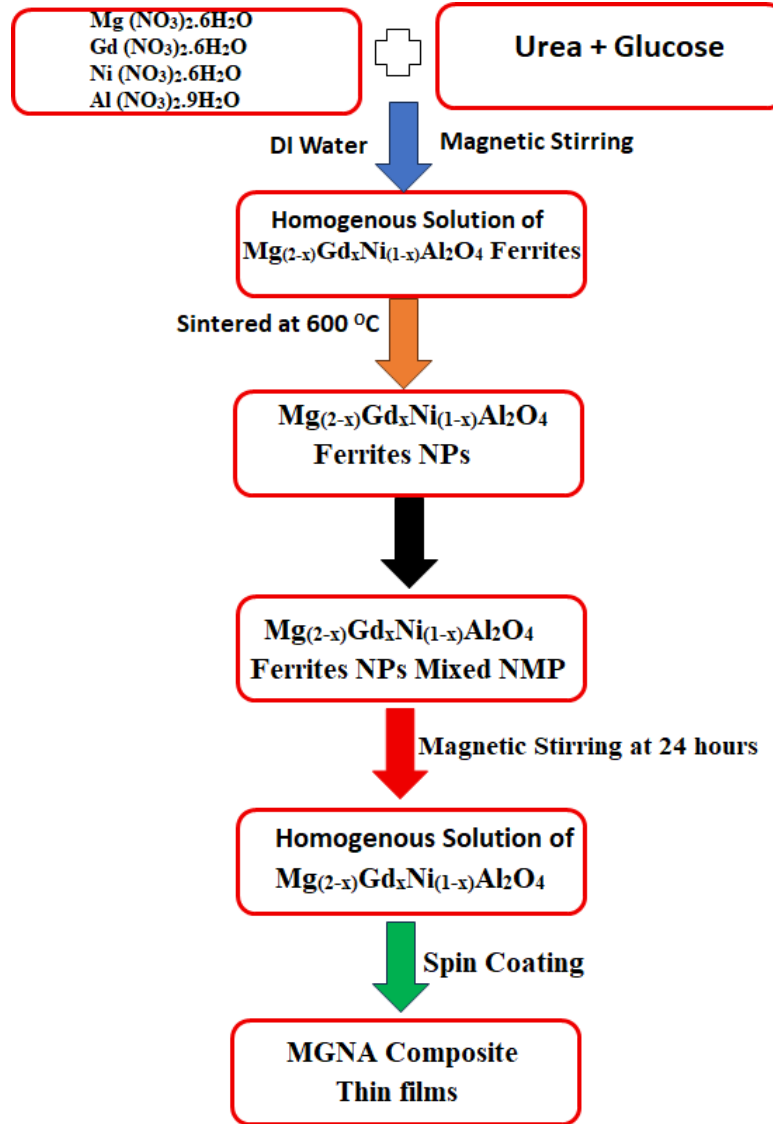


Figure. 1: Flowchart of synthesis of MGNA thin films.

3. Results and discussion

3.1 Micro structural and EDX analysis

The surface morphology MGNA ($x = 0.0, 0.25, 0.50$ and 0.75) composite thin films were carried out at room temperature are illustrated in the Figure. 2 (a-d). The figure 1(a) reflects the fact that formation of less micro grains across the ferrite thin film. The SEM micrographs of MGNA ($x = 0.25, 0.50$ and 0.75) composite thin films samples are displayed in the Figure. 2(b-d). The strong agglomeration of ferrites NPs was present in the Gd^{3+} doped $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ composite thin films reflects the fact that to improved magnetic features of the GMNA composite thin films. However, the agglomeration process was noticeably decreased with the inclusion of Gd^{3+} NPs in the host $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ spinel-ferrite composites thin films (Fig. 2d). This morphological modification was proved that by doping of small concentration of Gd^{3+}

NPs effectively controlled the strong aggregation of ferrites composites [21]. By doping of Gd^{3+} NPs into the host $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ ferrites composite, the surface morphology leads to more agglomerated which effects give the smooth transportation of charge carriers across the MGNA composite thin films. The present research work is demonstrated that the enhanced agglomerated surface morphology of the composite thin films is lead to the robust the electrostatic and magnetic dipole interactions in hybrid composite thin films. Hence, the SEM images of hybrid composite thin film was displayed enhanced particle size owing to the of the presence of variable functional groups like manganese, nickel and aluminate NPs present composite thin films [22]. The average grain size of MGNA composite thin film was found to be 45 nm. To validate the different elements, exist in the prepared MGNA composite thin films we are performed energy dispersive x-ray spectroscopy (EDX). The EDX plots of GCNF ($x=0.0$ and $x=0.75$) thin films samples are displayed in the Figure. 3(a-b). In pure ferrites thin film ($x=0.0$), the prime elements like manganese, nickel, aluminate and oxygen are exists in more concentrations. Similarly, in case of MGNA ($x=0.75$) composite thin film, the prime elements like gadolinium, manganese, nickel, aluminate and oxygen are present. The composition of the different elements calculated by using EDX method are well agreed with the stoichiometry method of calculation are illustrated in the Table.1. The EDX analysis was render the fact that none of the prepared ferrites composite thin films samples contain any kind of impurities and defects.

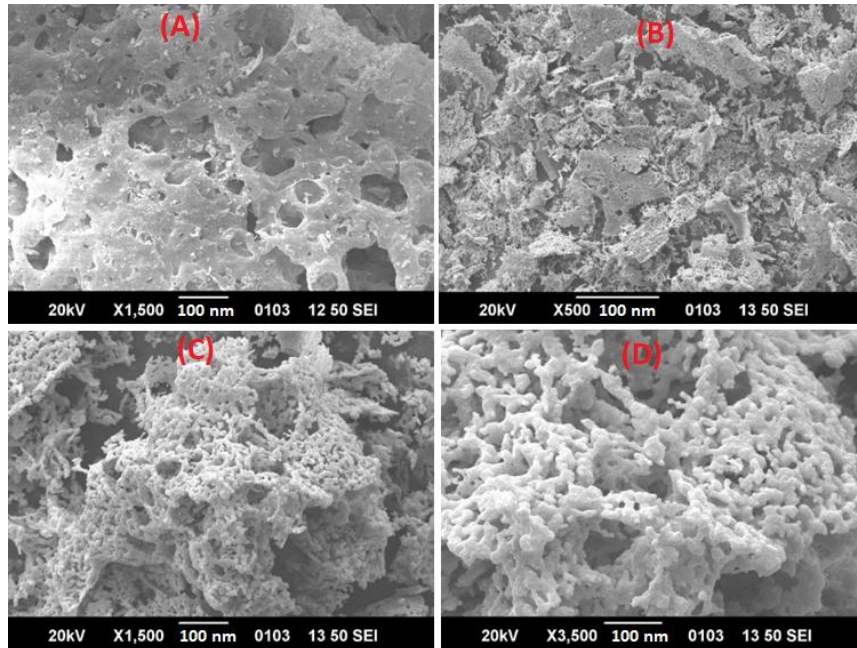


Figure. 2: SEM micrographs of (a) MGNA ($x=0.0$) (b) MGNA ($x=0.25$) (c) MGNA ($x=0.50$) (d) MGNA ($x=0.75$) thin film.

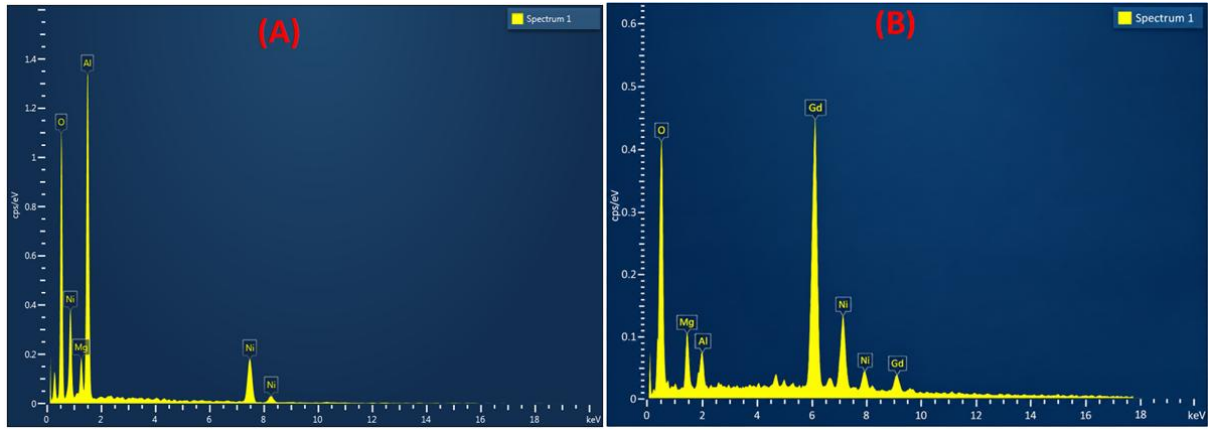


Figure. 3: EDX analysis of (a) MGNA (x=0.0) (b) MGNA (x=0.75) thin film.

Mg ²⁺ and Gd ³⁺ Concentration	Elements	Composition Theoretical	Composition EDX
X=0	Mg	2	2.0453
	Ni	1	1.0546
	Al	1	0.9984
	Gd	0	0.0000
X=0.25	Mg	1.75	1.7431
	Ni	0.75	0.7345
	Al	1	1.0453
	Gd	0.25	0.2345
X=0.50	Mg	1.50	1.4812
	Ni	0.50	0.5067
	Al	1	0.9884
	Gd	0.50	0.4923
X=0.75	Mg	1.25	1.2345
	Ni	0.25	0.2367
	Al	1	0.9454
	Gd	0.75	0.7345

Table.1: EDX analysis of MGNA (x = 0.0, 0.25,0.50 and 0.75) composite thin films.

3.2 X-ray diffraction analysis

To study the crystallinity features in the prepared MGNA composite thin films, we have carried out the X-ray diffraction tests at ambient temperature. The XRD pattern of MGNA (x= 0.0,0.25,0.50 and 0.75) thin films are presented in the Figure. 4 (a-d). From the XRD pattern we have validated that, the exitance of prominent peaks near to crystallographic plane (111), (220), (311), (400), (410), (422), (440) and (511) are signifies the spinal ferrites structure of MGNA ferrites composites films. These Miller indices are well agreed with the JCPDS Card number: 22-1086. The XRD pattern indicates the presence of Fd3m ionic partition and single phase in the synthesized ferrites composite thin films [23]. Increasing the concentration of Gd³⁺

NPs into the $\text{Mg}_{(2-x)}\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ spinel ferrites leads to the marginal change in the crystalline geometry of the MGNA composite thin films. In order to calculate the crystallite size, we have employed Scherrer's expression, the calculated value is good agreement with the grain size was determined via SEM characterization method.

$$D = \frac{k\lambda}{\beta \cos\theta} \quad (1)$$

where, D indicated the crystallite size, k represents the structure factor is near to the 0.9, λ represents the X-ray wavelength, β represents the full width half maximum of characteristic peak, and θ represents the angle of diffraction in order. The crystal lattice constant could be deliberated by employed the expression [24].

$$a = d \sqrt{h^2 + k^2 + l^2} \quad (2)$$

Where "d" represents the interplanar spacing in crystalline surface and (h, k, l) designates the Miller indices of the corresponding crystal planes respectively.

The dislocation density of NPs present in the synthesized MGNA composite thin films was determined by using the expression.

$$\text{Dislocation density} = \frac{1}{D^2} \quad (3)$$

Furthermore, we have utilised Bragg's equation to determine interplanar distance in crystal planes in most of large intense peaks exists in XRD pattern.

$$n\lambda = 2d\sin\theta \quad (4)$$

The calculated the aggregate crystallite size via XRD analysis by employed the Debye-Scherrer's equation was found approximately 51 nm. It is very interesting to observed that crystal lattice constants and crystal lattice dimension was marginally varies with the concentration of Gd^{3+} doping in $\text{Mg}_{(2-x)}\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$. The structural parameters of all synthesized thin films are displayed in the Table.2. It was curious to note from the XRD pattern both crystallite size and strains parameters are significantly enhanced with varying the concentration of Gd^{3+} NPs in $\text{Mg}_{(2-x)}\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ spinel ferrites. The increment in the crystallite size due to the exitance of improved crystalline features and excellent chemical composition exist in synthesized MGNA composite thin films.

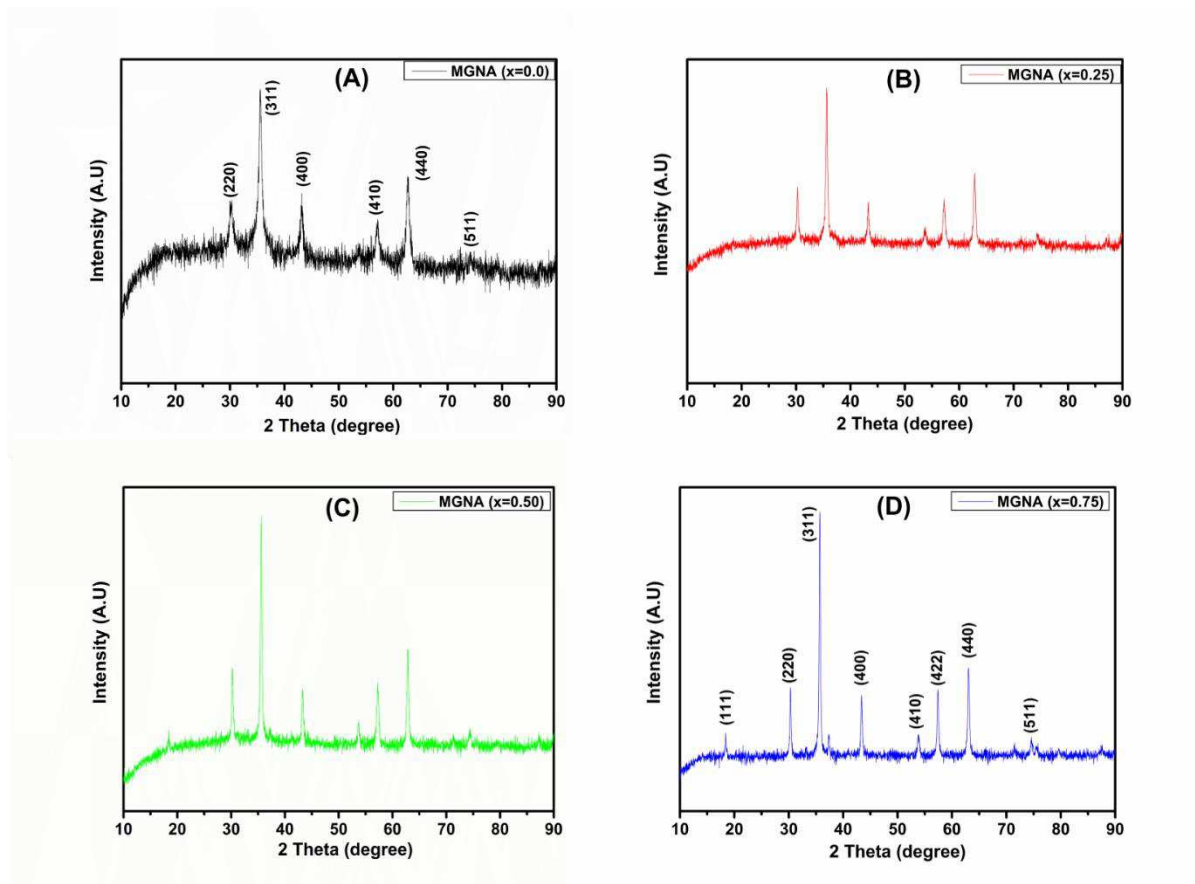


Figure. 4: XRD pattern of (a) MGNA ($x=0.0$) (b) MGNA ($x=0.25$) (c) MGNA ($x=0.50$) (d) MGNA ($x=0.75$) thin film.

Sl.No	Samples	Crystallite size (nm)	Lattice parameter ($\text{\AA}$)	d- Spacing ($\text{\AA}$)	Volume ($\text{\AA}^3$)	Dislocation density $\times 10^{-4} (\text{nm}^{-2})$	Lattice strain $\times 10^{-7}$
1	MGNA ($x=0.0$)	42	7.734	5.674	183.23	1.6623	2.134
2	MGNA ($x=0.25$)	49	7.812	5.863	245.76	1.9832	4.845
3	MGNA ($x=0.50$)	54	8.156	6.123	310.45	2.1256	5.145
4	MGNA ($x=0.75$)	58	8.216	6.324	350.81	2.4781	6.456

Table.2: Structural parameter of MGNA ($x=0.0, 0.25, 0.50$ and 0.75) composite thin films.

3.3 Fourier transform infrared spectroscopy (FTIR)

The variable functional groups present in MGNA (0.0, 0.25, 0.50 and 0.75) composite thin films are measured through FTIR characterization technique. In the present study, the FTIR spectra was recorded from 500 cm^{-1} to 4000 cm^{-1} wave number region. The recorded FTIR spectra of all synthesized MGNA composite thin films are depicted in the Figure. 5. The FTIR spectra displayed the fact that, strong optical absorption at stretching frequency bands close to 3416

cm^{-1} due to O-H vibrational band arises due to the absorption of moisture on the surface of thin film [25]. The prime vibrational peaks approximately at a stretching frequencies of 2371 cm^{-1} and 1633 cm^{-1} arises due to the Mg-O and Ni-O asymmetric vibrations modes [26]. The important vibrational peaks near to a stretching frequencies 1500 cm^{-1} and 1430 cm^{-1} due to the Gd-O and Ni-O symmetric vibrational modes. The significant stretching frequencies near to 1100 cm^{-1} , 840 cm^{-1} and 540 cm^{-1} is arises due to the rare earth metal ions plane vibrational bands exists in the MGNA composites ferrite thin film. The major conclusion of FT-IR characterization was the well dispersion of rare earth Gd^{3+} in $\text{Mg}_{(2-x)}\text{Ni}_{(1-x)}\text{Al}_2\text{O}_4$ spinal ferrites.

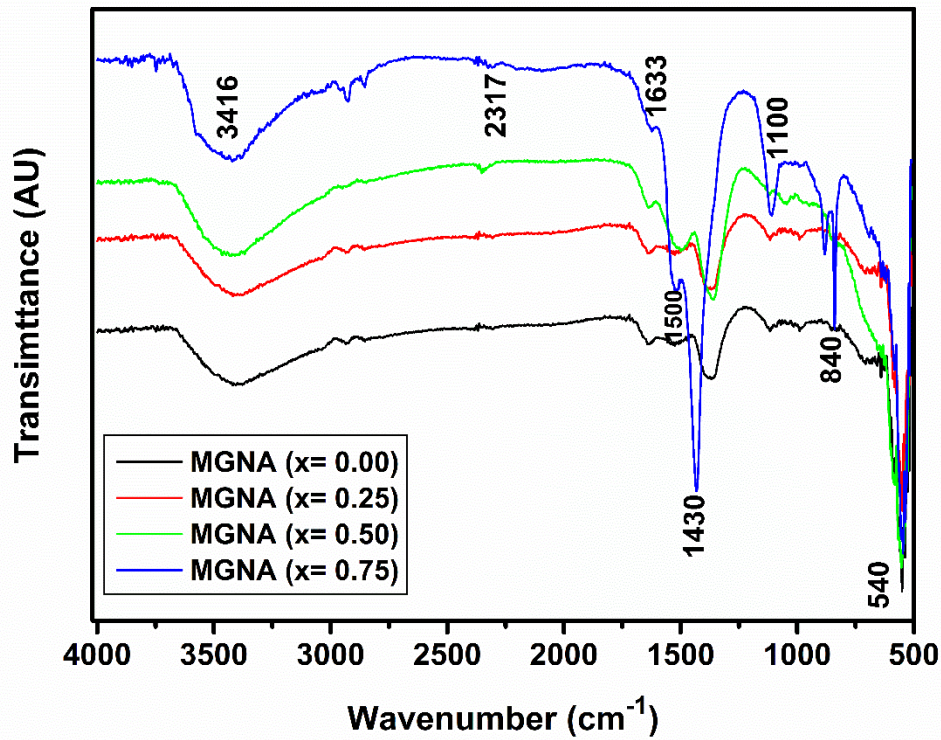


Figure. 5: FTIR spectra of (a) MGNA ($x=0.0$) (b) MGNA ($x=0.25$) (c) MGNA ($x=0.50$) (d) MGNA ($x=0.75$) thin film.

3.4 Ultraviolet visible study

The ultraviolet visible spectroscopic characterization is a prime tool to validate the optical absorption characteristics in most of the ferrites composites thin films. The optical absorption spectra of all synthesized ferrites ($x=0.0, 0.25, 0.50$ and 0.75) thin films are recorded at ambient temperature condition in the wavelength region of 330 nm to 600 nm . The UV-visible spectra of all synthesized MGNA composites thin films are illustrated in the Figure.6(a). The optical

absorption properties in the ferrites composites thin films largely influenced by many factors which includes particle size, lattice strain, presence of impurities, and surface defects [27]. The optical absorption peaks shown that the photons are predominately absorbed at ultraviolet zone near to 420 nm, this particular wavelength come under the visible region of the wide electromagnetic spectrum of light. Therefore, photo-excitation and de-excitation mechanism of electron take place between the valence and conduction bands was noticed in the synthesized MGNA composite thin film. But, a very clear blue shift was observed in the prepared ferrites composite thin films. The enhancement in the intensity of the optical absorption peaks in the MGNA ferrite thin films could be ascribed to the incorporation of Gd^{3+} ions into the ferrite lattice, which modifies the local crystal structure, cation distribution, and lattice vibrations. The more ionic radius of Gd^{3+} elucidated with the host cations promotes the lattice distortion and increases structural disorder, resulting in stronger vibrational interactions and enhanced infrared absorption. In particular, Gd^{3+} substitution can modify the Ni–O bond local environment and increase the dipole moment linked with metal–oxygen vibrations, thereby improving the intensity of the characteristic optical absorption bands [28]. Subsequently, the progressive increase with increases in Gd^{3+} concentration could lead to more optical absorption peaks, reflecting the major changes in the structural and vibrational features of the MGNA ferrite thin film. The prime reason for the modification in the UV-visible spectra of the ferrites composite thin films is due to the improved surface morphology, particle size, and micro structures that present in the highest content of Gd^{3+} doped $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ ferrite composite thin films. In general, the substantial improvement in the intensity of the UV-visible spectra of the highest MGNA ($x = 0.75$) composite thin films in compare to the pristine MGNA ($x=0.0$) thin film.

3.5 Thermogravimetric analysis

In order to examine the thermal degradation features of the prepared MGNA composites thin films samples, we have done the thermogravimetric tests. TGA tests are recorded at by heating the samples at a constant rate of $10^{\circ}C/minute$ at room temperature to $800^{\circ}C$ in presence of nitrogen gas environment. Thermogram of MGNA ($x=0.0$ and $x=0.75$) composite thin films are illustrated in the Figure.6 (b). The enhanced thermal stability of MGNA composite thin films can be ascribed to the doping of Gd^{3+} ions into the spinel ferrite lattice, which strengthens the metal–oxygen bonds and increases the lattice energy [29]. In addition, the presence of Gd^{3+} modifies the cation distribution between tetrahedral and octahedral sites and enhances the

structural rigidity of the spinal ferrite matrix [30]. Consequently, Gd^{3+} doping inhibits the formation of thermally induced defects and improves the resistance of the MGNA composite thin film lattice to thermal decomposition, resulting in superior thermal stability in MGNA ($x=0.75$) composite thin film. The synthesized MGNA thin films are shown weight loss behaviour in three variable steps. The first step of weight loss take place nearly (7wt.%) was recorded near to $100^{\circ}C$ reflects the exitance of moisture present in the prepared thin films. In second stage of weight loss mechanism, thin films show slow weight loss at the temperature around $450^{\circ}C$ and $600^{\circ}C$ due to the presence of manganese, nickel, gadolinium and aluminate NPs in the composites thin film. Similarly, in third stage the residual degradation mechanism begins from the $700^{\circ}C$. The net degradation of the weight of MGNA composite thin film was recorded near to 20 wt.%.

Amid the prepared samples, the MGNA ($x=0.75$) thin film was exhibited excellent thermal stability in comparison with the pristine MGNA ($x=0.0$) thin film which is close to 60% weight loss. Therefore, in the current study we have selected the sintering temperature around $500^{\circ}C$ to prepare the MGNA spinal ferrite NPs.

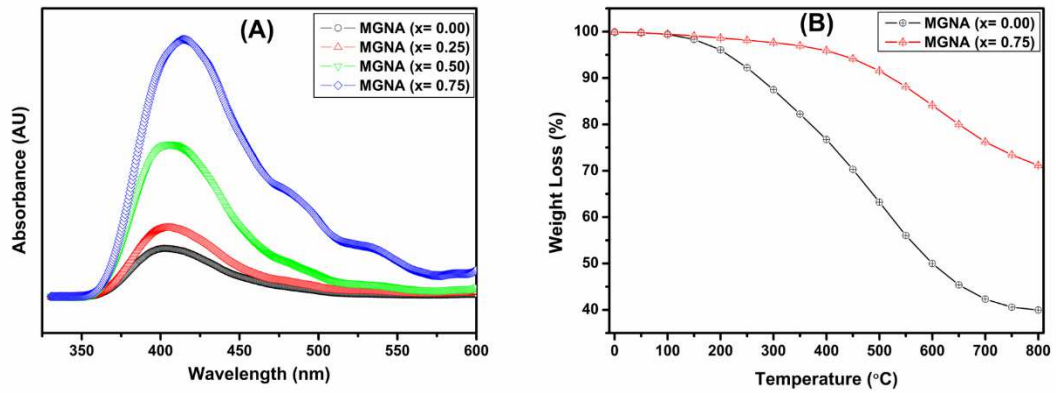


Figure. 6: (A) UV-visible spectra of (a) MGNA ($x=0.0$) (b) MGNA ($x=0.25$) (c) MGNA ($x=0.50$) (d) MGNA ($x=0.75$) thin film. (B) TGA spectra of (a) MGNA ($x=0.0$) (b) MGNA ($x=0.75$) thin film

4. Electrical conductivity study

The spinal ferrites composite thin films are play an important role in the design of EMI shielding equipment worked at ambient temperature. The conductivity of the prepared MGNA ($x=0.0, 0.25, 0.50$ and 0.75) composite thin films was computed by using an equation [31].

$$\sigma = \frac{d}{RA} \quad (5)$$

Where “R” designated as resistance and “d” be the thickness and “A” be the the surface area of thin film.

The trend of variation of electrical conductivity of MGNA ($x=0.0, 0.25, 0.50$ and 0.75) composite thin films with a step of subjected temperature are displayed in the Figure.7. The electrical conductivity of the MGNA composites thin films are mainly depending on the structural and surface morphology modifications in the highest MGNA ($x=0.75$) thin film sample. Hence, by doping of Gd^{3+} into the $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ spinal ferrites is one of the effective methods to improve the electrical conductivity in MGNA composites thin film. It was noticed from the SEM micrographs of pristine and MGNA ferrites composite thin films are helps in phase segregations of $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ and Gd^{3+} which effects leads to the improvement in the intra chain charge carrier hopping between favourable sites of MGNA ferrites thin films domains. The conductivity of MGNA ferrite thin films increases significantly with varying the temperature and Gd^{3+} content, which can be assigned to the thermally activated hopping of charge carriers between localized sites of Ni^{2+} and Mg^{2+} ions at the octahedral position. Doping of Gd^{3+} ions in $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ lattice alter the cation distribution, defect content, and oxygen-vacancy number, thereby facilitating the easy charge transport via the ferrite crystal lattice. The enhancement in temperature gives the enough thermal energy for localized charge carriers to overcome the activation energy and involved successfully in electron hopping, which results in improved conductivity was observed [32]. Moreover, an optimum content of Gd^{3+} could enhances the structural defects and reduction in the hopping distance, over all these mechanisms turn into the enhanced electrons mobility, leading to a progressive enhancement in conductivity. Among the prepared thin MGNA film, MGNA ($x =0.0$) thin film exhibit lowest about 15.76 S/cm and MGNA ($x =0.75$) composite thin film displayed conductivity about 120 S/cm respectively.

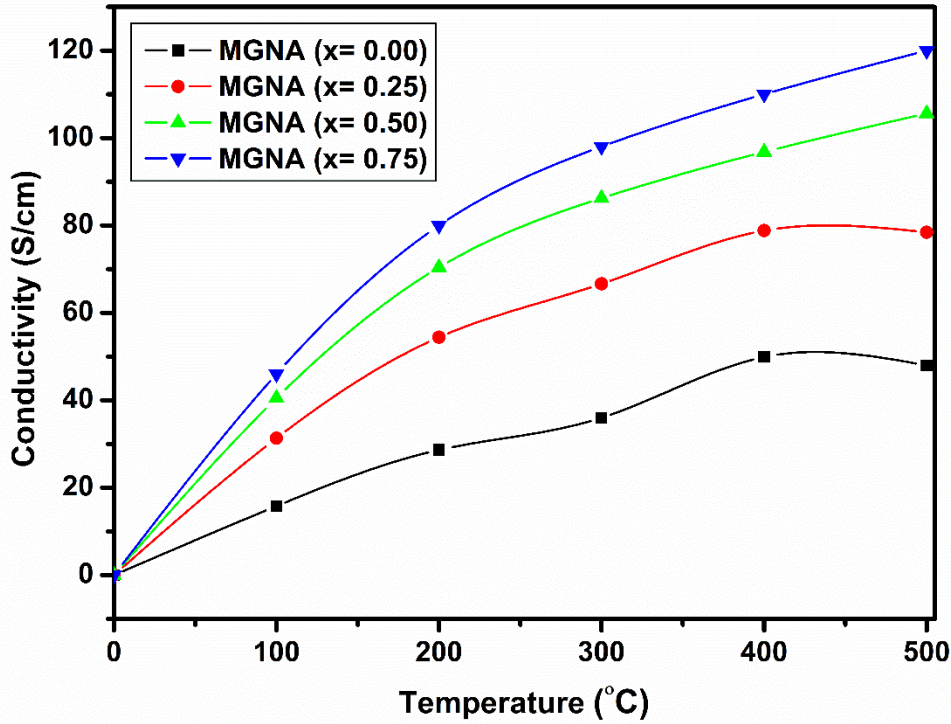


Figure. 7: Temperature dependent conductivity (a) MGNA ($x=0.0$) (b) MGNA ($x=0.25$) (c) MGNA ($x=0.50$) (d) MGNA ($x=0.75$) thin film.

5. Dielectric studies

5.1 Dielectric and magnetic spectroscopy

By employed dielectric and magnetic spectroscopic studies we have studied the charge migration properties in the synthesized spinal ferrites composites thin films. The dielectric parameters with respect to permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and magnetic permeability features with respect to ($\mu_r = \mu' - j\mu''$) are recorded at the microwave frequency zone (8GHz to 18GHz) to explain the feasible EM shielding applications in the synthesized spinal ferrite composite thin films [33]. The permittivity (ϵ' and ϵ'') and permeability (μ' and μ'') values of the ferrites composite thin films are determined by employed advanced “Nicolson-Ross-Weir (NRW) method “which consists of one port to measure the S-parameters. In particular, S-parameter also designated as scattering parameters like S11/S22 and S12/S21. The S-parameters in the ferrites composite thin films are measured by using vector network analyser (VNA) by irradiating and transmitted the EM wave inside the VNA via which permittivity and permeability values are calculated. As per the concept of electromagnetic theory both the ϵ'

and μ' shows the microwave energy storage ability of the composite thin film, whereas ϵ'' and μ'' signifies the microwave energy loss in the ferrites composite thin film [34]. The change of both real and imaginary components of permittivity with subjected frequency in case of MGNA ($x=0.0, 0.25, 0.50$ and $x=0.75$) composite films were displayed in the Figure. 8 (a and b). It is curious noted both the of dielectric constants values are close to constant values over the whole microwave frequency region. In the commencing stage the increment in the real and imaginary component of dielectric constant due to the formation of more population of nano dimension capacitors due to the polarization mechanism produced in the composite thin film [35]. The creation of capacitive kind of networks between the magnesium-nickel and gadolinium-aluminate NPs with larger volume to surface ratio can turns to the enhanced polarization at the area of the grain boundaries which render the improved ϵ' and ϵ'' values for $x=0.75$ composite film. The improved charge density in the MGNA ($x=0.75$) sample leads to the improved polarization mechanism with additionally the interactions of dipoles close to the grain boundaries with the aid of micro wave frequencies, these consequences give the improved dielectric features of the synthesized ferrites composite thin films. Doping of Gd^{3+} NPs into $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ spinal ferrites turns to the enhanced conducting paths which boost the polarization process which effects the enhanced both real and imaginary permittivity values in case of $x=0.75$ composite films.

The variation of real and imaginary components of magnetic permeability (μ' and μ'') with a step of subjected microwave frequencies for all prepared ferrites composite thin films are displayed in the Figure. 8 (c and d). The real and imaginary components of magnetic permeability values shown close constant over the applied microwave frequency region. Pertained to the dielectric attributes of both real and imaginary components of permeability (μ' and μ'') exhibit strong dependency over the manganese, nickel, gadolinium and aluminate NPs content in the prepared composite film. So, the nickel and Gd^{3+} NPs largely magnetic in nature by adding this kind of NPs in the manganese and nickel spinal ferrites produces the interfacial magnetic dipole moments which results in improved permeability features of the ferrites composite film [36]. The noticeable increment in the both real and imaginary components of permeability in the zone of high frequencies may be owing to the strong coupling of the magnetic dipoles with subjected microwave frequencies. At higher frequencies zone, inside the composite thin films produces the magnetization properties which lead to the robust the

magnetic dipole coupling, these effects might be a noticeable increment in real and imaginary component of permeability of the composite thin film [37].

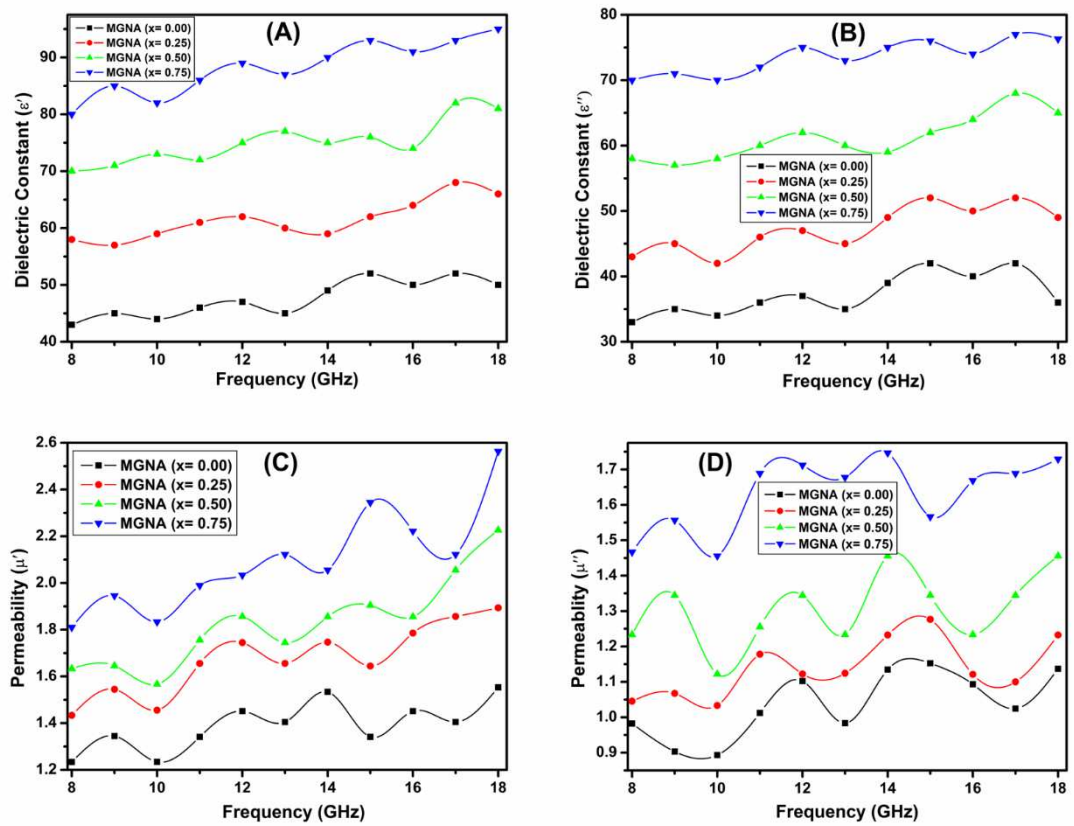


Figure.8: (a-b) Variation real and imaginary part of permittivity and (c-d): Variation real and imaginary part of permeability of MGNA ($x=0.0, 0.25, 0.50, 0.75$) composite thin films.

5.2 EMI-shielding studies

“The electromagnetic interference (EMI)” is normally distinct as the attenuation produced by the incoming microwaves via the different physical mechanism like absorption, reflection and transmission of electromagnetic waves. During the EM waves of travel inside the shielding material of incident power (P_i), some part of EM waves is transformed into the reflected (P_r), absorbed (P_a) and transmitted wave of power (P_{tr}) respectively. The feasible physical mechanism of the interface of electromagnetic (EM) waves inside the shielding material is illustrated in the in the Figure.9(a). In particular, EMI shielding mechanism was involved by two main physical phenomenon such as absorption and reflection process inside the shielding equipment [38]. When the EM wave interacts with the shielding material, some components of EM wave is reflected because of the interface with the present charges on the surface and some

component of EM waves is transmitted in addition to penetrates at the core of the shielding material which results energy ejected through absorption mechanism [39]. The block diagram of EMI shielding measurement equipment used in the current study is showed in the Figure.9(b). The high-powered EM waves interface with shielding material in terms of power can be represented by employed the equations.

$$(P_t) = (P_r) + (P_a) + (P_{tr}) \quad (6)$$

The attenuation of electromagnetic (EM) radiations is propagating through a shielding material is commonly called as electromagnetic interference shielding effectiveness (EMI-SE). This parameter provides a quantitative measure of the ability of a material to reduce the intensity of incident electromagnetic radiation and can be expressed using the following equation [40].

$$SE \text{ (dB)} = -10 \log (P_{in}/P_{tr}) \quad (7)$$

In the above expression P_{in} be the irradiated EM wave power and P_{tr} indicated transmitted EM wave power respectively.

The complete EMI-SE parameter was determined by employed the equation.

$$SE_T = SE_R + SE_A + SE_M \quad (8)$$

In case of EMI-shielding materials, the shielding effectiveness (SE_T) can be calculated by adding the reflection (SE_R), absorption (SE_A) and multiple reflection (SE_M) of incident EM waves at inside the shielding material. In specific, the SE_T greater than 10 dB, SE_M turns to the experimentally less important. Therefore, the total SE would modify to below equation.

$$SE_T = SE_R + SE_A \quad (9)$$

By employing the scattering parameters such as S_{11} and S_{12} was measured by utilised vector network analyser (VNA), the reflection (R) and transmission (T) coefficients can be evaluated by employed the equation.

$$R = |S_{11}|^2 \text{ and } T = |S_{21}|^2 \quad (10)$$

By using the reflection and transmission EM wave we have determined the absorption coefficient parameter (A) of the shielding material by using the equation.

$$A + R + T = 1 \quad (11)$$

In addition to series internal reflections of EM waves between the shielding material at the interface of active area, the EM waves energy more depends over the (1-R). The absorption coefficients of EM waves can be denoted with the equation.

$$A_{\text{eff}} = (1-R-T)/(1-R) \quad (12)$$

The reflection and strong absorption co-efficient of EM waves can be determined in terms of decibel (dB) by employed the following equations.

$$SE_R = 10 \log (1-R) \quad (13)$$

$$SE_A = 10 \log (1-A_{\text{eff}}) = 10 \log [(T/(1-R))] \quad (14)$$

The skin depth parameter of EM waves is defined as the transmitting power EM waves which is transmitted core region of the shielding equipment. The skin depth could be determined by consideration of both electrical and magnetic parameters like conductivity, permeability and penetrated microwave by using the equation.

$$\delta = \frac{1}{\pi f \mu \sigma} \quad (15)$$

The attenuation co-efficient parameter of EM waves was calculated by using the below equation.

$$\alpha = \frac{\sqrt{2\pi f}}{c} \times \sqrt{((\mu''\epsilon'' - \mu'\epsilon') + \sqrt{(\mu\epsilon'' - \mu'\epsilon')^2 + (\mu'\epsilon'' + \mu''\epsilon')^2})} \quad (16)$$

Where “C” represents the speed of light and “f” be the frequency of EM wave.

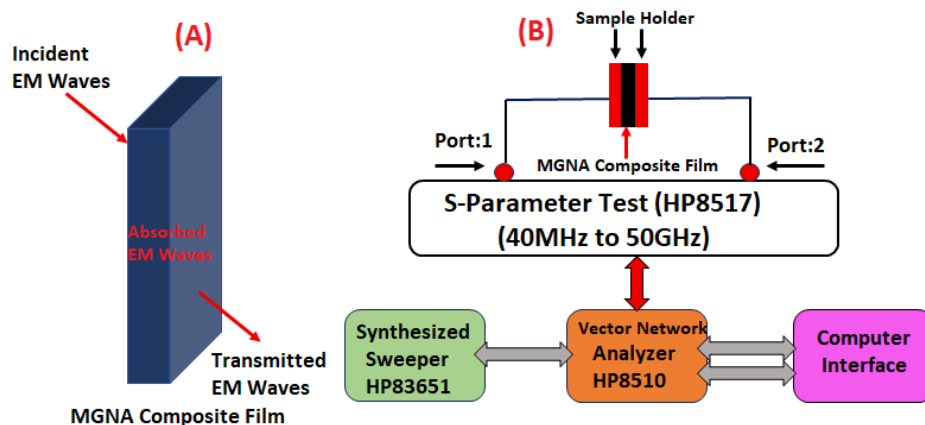


Figure.9: (a) Schematic representation of interaction of EM waves with shield material (b) Block diagram of Vector Network Analyser.

The variation of reflection and absorption co-efficient for MGNA ($x=0.0, 0.25, 0.50$ and 0.75) composite thin films are displayed in the Figure.10 (a and b). The prepared samples are exhibited absorption dominated shielding features instead of the reflection features over the applied microwave frequencies region [41]. From the plots we can observed that absorption of EM wave increased noticeable, similarly, the reflection coefficients values are slightly reduced with a step of microwave frequency. The absorption dominated characteristics can be connected with the increasing the doping of Gd^{3+} and Mg^{2+} NPs in spinal ferrites composite thin films which facilitated to robust dielectric properties and magnetic attenuation feature. The strong absorption dominated characteristics leads to the loss in electromagnetic energy in the form of heat due to the on and off mechanism of an electric dipoles exist in the composite thin films. The dielectric and magnetic attenuations are arising in the composite thin films might be due to the greater conductivity and improved morphology of the composite film. Similarly, the magnetic attenuation may be produced due to permeability exists in the composite thin film. Hence, the magnetic attenuation in the composite thin films have been exceptional features such as absorption dominated absorption features in comparison with advanced materials which possess larger dielectric loss with applied frequencies. Hence, the composite thin films with improved electrical conductivity and least magnetic permeability displayed predominated reflection attenuation in nature. Thus, the MGNA composite thin films investigated in the present study exhibited higher permeability values, indicating that they function predominantly as absorption-dominated EMI shielding materials, particularly in the microwave frequency range. The reflections dominated properties of the composites thin film material is mainly depend over the σ/μ ratio. The improved dielectric and magnetic features of the composites thin films are largely contributed towards the absorption dominated EMI shielding properties [42]. The prepared composite thin films are demonstrated the considerable potential for commercial applications, particularly in radar and defence-related technologies.

The EMI-SE with a function of applied microwave frequencies for MGNA ($x=0.0, 0.25, 0.50, 0.75$) thin films are illustrated in the Figure.10 (c). The prepared composite thin films are shown nearly same SE features with a step of microwave frequency region. The absorption dominated EMI-SE in the synthesized composites thin films can be obtained because of the dielectric as well as the magnetic attenuation of the spinal ferrite composite thin films [43]. The presence of magnesium, nickel and aluminium NPs and doping of Gd^{3+} rare earth NPs in composite thin films facilitated the improved conductivity and magnetic permeability characteristics of the

composite thin films. The dielectric ($\epsilon_r = \epsilon' - j\epsilon''$) and permeability parameters ($\mu_r = \mu' - j\mu''$) are largely influence on microwave energy liberation. Furthermore, the improved permeability of the composite thin films is created the magnetic dipoles coupling which leads to the magnetic attenuation of EM waves, these special features of the spinal ferrites composite thin films helps to the absorption dominated shielding feature [44]. By doping of nano dimensioned Gd^{3+} ferrite NPs renders multiple grain boundary interfaces, which encourage a greater number of scattering and absorption of EM waves. Rare-earth doping is well known to majorly varied the dielectric, and electromagnetic features of spinel ferrites composites films via the lattice distortion and structural modifications. So, the improved EMI-SE with varying the Gd^{3+} contents could sensibly be ascribed to the total effects of enhanced dielectric polarization, charge-carrier conduction, magnetic loss, and multiple internal reflections, resulting in stronger attenuation of the incident EM radiation. It was noticed that, in microwave frequency region, the prepared MNGA composite thin films exhibited enhanced dielectric and magnetic feature which results turn into the superior EMI-SE performance. The EMI-SE improved form – 20.23 dB for GMNA ($x=0.0$) thin film and close to the – 26.25 dB for GMNA ($x=0.75$) composite thin film. According to the industrial needs and economical standard rules SE of – 26.25 dB which close to the 99.89% shielding effectiveness. In our current investigation we validated that, the ferrites composite thin films can be utilised as probable material for effective shielding applications especially in radar and military applications.

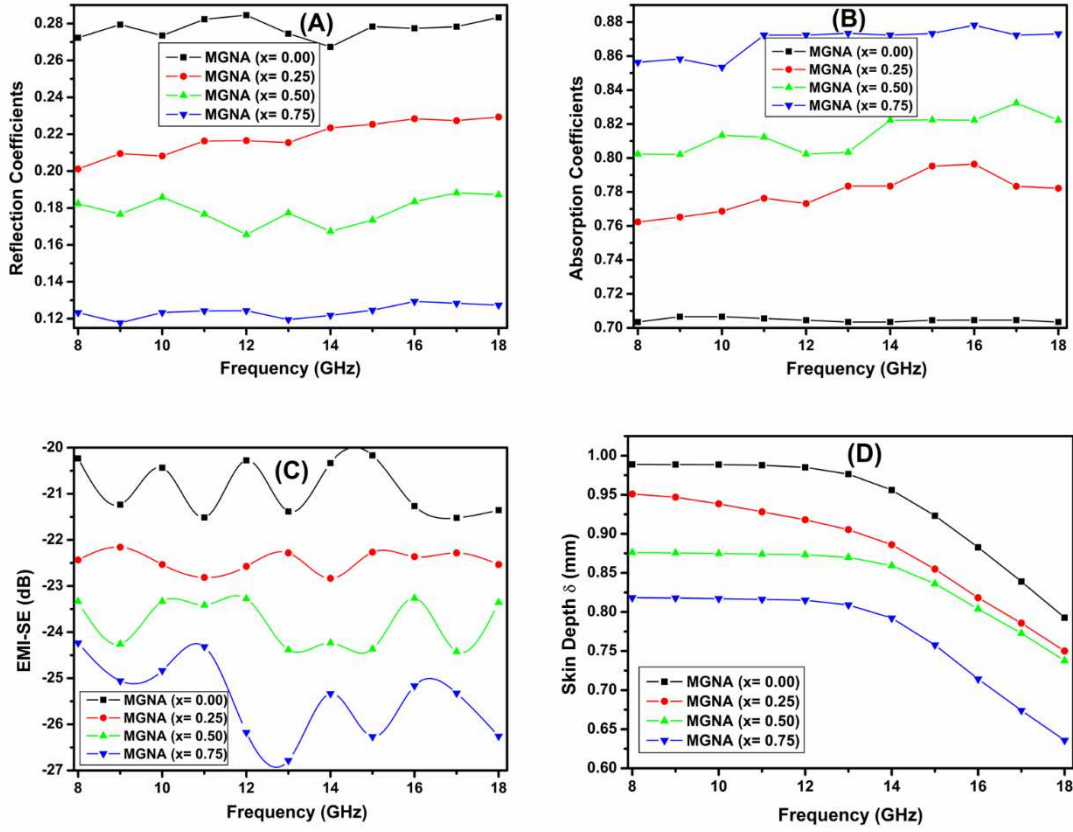


Figure.10: (a) Variation of reflection co-efficient (b) absorption co-efficient (c) EMI-Shielding efficiency and (d) Skin depth for MGNA ($x=0.0,0.25,0.50,0.75$) composite thin films.

The skin depth is a prime parameter in the study of EMI shielding study, since this parameter is connected with the EM wave propagation which incident over the surface of conductor. This parameter is playing a significant role in majority of the power production units, radar and military applications. In specially, the skin depth (δ) can be utilized to record the ability of EM waves transmitted in the core of the shielding device. It changes inversely with the conductivity of the composite thin films. By doping of Gd^{3+} NPs into the $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ ferrite thin films, the interface and gaps are produced which increases the more absorption of EM waves owing to the series of internal reflections within the shielding device [45]. The variation of skin depth with a step of microwave frequency for all synthesized composite thin films are depicted in the Figure.10 (d). From the figure we can interfere that, the skin depth values of all prepared composite thin films are slightly decreases with increasing the microwave frequency. The main reason for reduction of skin depth values could be due to the doping of Gd^{3+} NPs into $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ composite film which replicates the fact that

more EM waves absorption ability of the composite thin film. Amid the synthesized thin films, the highest skin depth value was found to be GMNA ($x=0.0$) sample about 0.98 mm and lowest value is found to be in case of GMNA ($x=0.75$) sample the value was close to the 0.63 mm. This kind materials can be considered a promising material in manufacturing of EM shielding equipment which is worked at high frequency region at ambient temperature.

The long-term EMI-SE stability tests for GMNA ($x=0.75$) composite thin film was studied throughout the duration of 60 days as illustrated in the Figure.11 (a). From the plots, it was fascinating to note that for GMNA ($x=0.75$) composite thin film, EMI-SE was found to be nearly constant with negligible loss (2%) over a period of two months on exposure to high frequencies radiation. The EMI-SE data reflects the fact that, these composite thin films are do not suffers much degradation mechanism under the exposure of harsh atmosphere.

The attenuation parameter (α) indicates the capability of a material thin films to attenuate the incoming electromagnetic (EM) waves. The calculated attenuation constant is displayed in the Figure.11 (b). It is related with the dielectric and magnetic losses. From the plots one can interfere that the attenuation constant value increases with the loading of Gd^{3+} content in $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ spinel ferrite composite thin film. Which could be ascribed to the improved interaction of incident electromagnetic waves with the improved magnetic and dielectric values of the prepared composite films. Doping of Gd^{3+} rare earth metal into the host $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ ferrites turns to the lattice displacement, defects, and modifications in the cation distribution, which can robust the magnetic losses via increased domain-wall moments and spin mechanisms. In particular, doping of Gd^{3+} rare earth metal ions can improve the conductivity and polarization in spinal ferrites host matrix, thus enhancing the dielectric tangent loss and polarization mechanism. The net increment of dielectric and magnetic loss phenomenon endorses larger conversion of EM energy into the heat, which effects leads to the larger attenuation capability and robust EM wave absorption with enhancing the content of Gd^{3+} into the host $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ composite. Amid the prepared ferrites composites thin films MGNA ($x=0.75$) composite thin film exhibit highest attenuation constant in the order of 1806 dB/m in comparative assessment with the MGNA ($x=0$) sample nearly 235 dB/m. The high value of the attenuation constant in most of the spinal ferrites composite thin films are advantageous for EMI shielding applications [46].

The trend of eddy current losses with a function of microwave frequencies for MGNA ($x=0.0$ and $x=0.75$) composite thin films are displayed in the Figure.11 (c-d). The magnetic component of loss of energy of irradiated EM wave is referred to the eddy current loss [47]. In

lower frequency zone, the eddy current losses are very low due to the ferrites composite domain wall resonance, at the same time at the higher frequency zone, the eddy current loss suddenly increases and become stable at higher microwave frequency region [48]. In particular, the ferrites composite thin films have more eddy current losses due to the existence of higher resistivity exists in the composite thin films. By doping Gd^{3+} NPs into the $Mg_{(2-x)}Ni_{(1-x)}Al_2O_4$ ferrites, the eddy current losses get reduced considerable. Among the prepared composite thin films, lower eddy current losses were found to be for MGNA ($x=0.75$) composite thin film about 0.365 and higher for MGNA ($x=0.75$) composite thin film was nearly 0.958 between the frequencies zone 14 GHz to 16 GHz respectively.

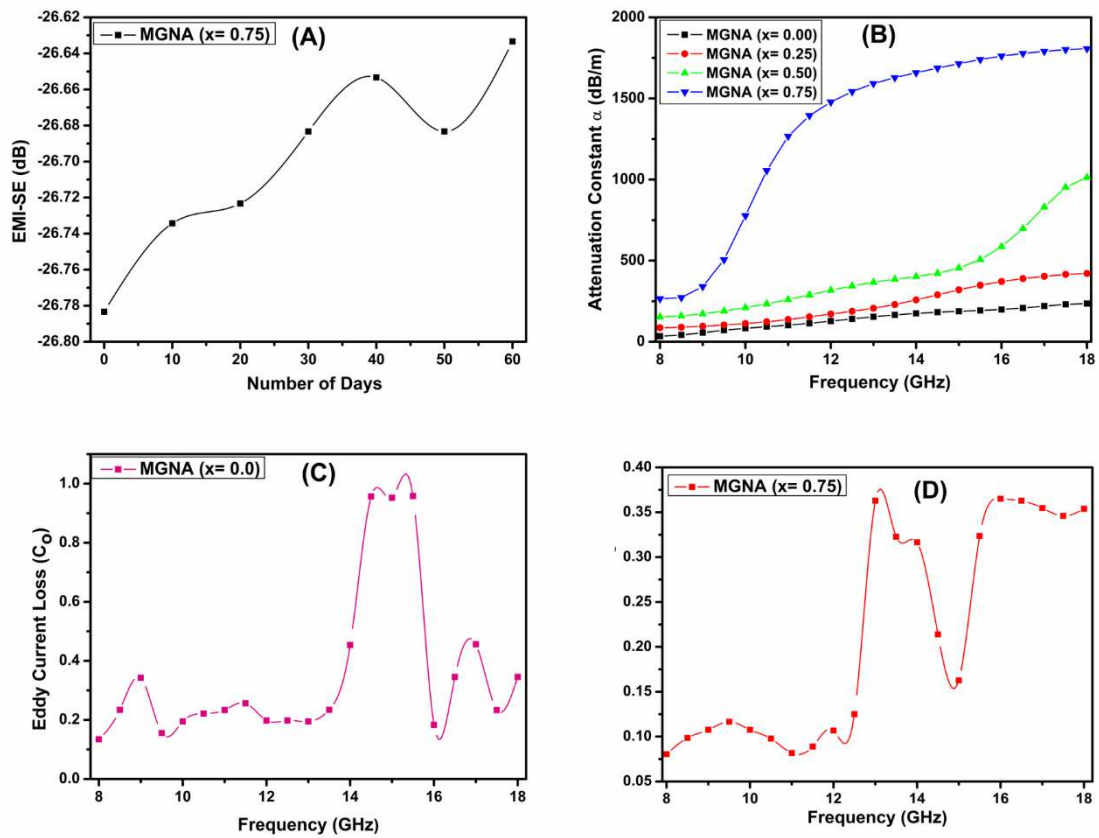


Figure.11: (a) Variation of EMI-SE stability test for MGNA ($x=0.75$) composite thin film (b) Attenuation constant for MGNA ($x=0.0, 0.25, 0.50, 0.75$) composite thin films (c) Eddy current loss for MGNA ($x=0.0$ and 0.75) thin films.

6. Conclusion

In conclusion, we have successfully synthesized the MGNA composite thin films by low-cost solution combustion method. The structural, morphology, compositional and thermal investigations were carried out using SEM, EDX, XRD, FTIR, UV-visible and TGA techniques.

Amid the prepared samples MGNA ($x=0.75$) composite thin film displayed highest electrical conductivity about 120 S/cm. This improvement in conductivity was associated with the increased concentration and mobility of charge carriers, which facilitates more efficient charge transport through composite film. Consequently, the enhanced electrical conductivity contributes to better interaction with electromagnetic radiation and improves the overall EMI shielding performance of the device. The dielectric attributes and magnetic permeability values showed that Gd^{3+} doping was significantly influenced the electrical polarization and magnetic response of the prepared composite thin films. The enhanced magnetic properties in MGNA composite thin films contribute to improved interaction with incident electromagnetic radiation through dielectric and magnetic loss processes. Consequently, the EMI shielding characteristics of the composite thin films were improved with Gd^{3+} incorporation, indicating their ability to attenuate unwanted electromagnetic radiation. Amid the prepared thin films samples MGNA ($x=0.75$) thin film displayed the improved dielectric, magnetic features, low eddy current loss and strong absorption dominated EM shielding features about -26.25 dB, this value close to 99.89 % of shielding efficiency under applied microwave frequency. In general, MGNA composite thin films exhibit a combination of structural, thermal, optical, dielectric and magnetic properties that make them promising candidates for EMI shielding technology to protect the instruments both in digital electronic and communication systems against to harsh electromagnetic radiation.

CRedit authorship contribution statement

Koushalya P.R: Supervision and validation of data, **Prathibha B.S:** Acquiring characterizations data and analysis, **Manjunatha.S.O** Materials characterizations, **Gurumurthy T.M** Writing-Review and editing the manuscript, **Latha A.L:** Conceptualization and formal analysis of characterization data, **Ravikumar.H.C:** Editing the final manuscript, **Syed Saleem Pasha:** Formal analysis of experimental data and Methodology, **Apsar Pasha:** Writing the original manuscript.

Acknowledgement

The authors are grateful to the Vision Group on Science and Technology (VGST), Department of Electronics, IT, BT and S&T, Government of Karnataka, for providing financial assistance under the K-FIST L2 scheme (GRD No. 1132). This support was instrumental in developing research infrastructure in the Department of Physics, Don Bosco Institute of Technology, Bangalore-560074.

Data availability

Data will be made available on request.

Declaration of Competing Interest

Authors listed in the manuscript certify that they have NO affiliations with or involvement in any Organization or entity with any financial interest or non-financial interest in the subject matter or Materials discussed in this manuscript.

References:

1. K. S. Mary Linsa , Viji C.; Roshila K. Pavithran; R. Rohith; Sreekanth J. Varma , Subodh Ganesanpotti, K. S. Sibi; U. S. Sajeev, Frequency-stable green EMI shielding in polyaniline-ferrite nanocomposites *via* dielectric and magnetic tuning, *RSC Adv.* (2025) 15 (39): 32654–32666. <https://doi.org/10.1039/d5ra04475h>
2. Kruželák, J., Džuganová, M., Plavec, R. *et al.* The effect of soft magnetic ferrites and carbon allotropes on EMI absorption shielding performance and mechanical characteristics of NBR-based composites. *emergent mater.* 9, 164 (2026). <https://doi.org/10.1007/s42247-026-01461-0>
3. Z. Ma, S. Zhang, Z. Duan, Y. Li, Electromagnetic interference effect of portable electronic device with satellite communication to GPS antenna. *Sensors.* **25**(14), 4438 (2025)
4. Y. Huang, M. Chen, A. Xie, X. Xu, Recent advances in design and fabrication of nanocomposites for electromagnetic wave shielding and absorbing. *Materials.* **14**, 4148 (2021)
5. R.S. Yadav, I. Kuřitka, Recent developments on nanocomposites based on spinel ferrite and carbon nanotubes for applications in electromagnetic interference shielding and microwave absorption. *Crit. Rev. Solid State Mater. Sci.* **49**(3), 371–407 (2024)
6. S.S. Atkare, S.T. Alone, A.V. Fulari, V.N. Dhage, R.H. Kadam, S.E. Shirsath, M.L. Mane, Design of multifunctional rare earth Dy–Ce substituted BaFe₁₂O₁₉ nanoparticles for X-band microwave absorption and EMI shielding. *Inorg. Chem. Commun.* **179**, 114805 (2025)
7. C. Lei, Y. Du, Tunable dielectric loss to enhance microwave absorption properties of flakey FeSiAl/ferrite composites. *J. Alloys Compd.* **822**, 153674 (2020)
8. C. Shao, H. Liu, Y. Shi, N. Tian, C. You, Z. Zhao, Dielectric-magnetic synergy in ferrite/carbon composites for electromagnetic microwave absorption. *Nano Res.* (2025). <https://doi.org/10.26599/NR.2025.94907815>
9. M.S. Hareesh, P. Joseph, S. George, Electromagnetic interference shielding: a comprehensive review of materials, mechanisms, and applications. *Nanoscale Adv.* **7**, 4510 (2025)
10. Q. Xia, B. Liu, T. Wang, T. Liu, P. Cui, W. Song, G. Song, Y. Wang, X. Wang, Lightweight and flexible CNT/PEI/Fe₃O₄ composite films with high EMI shielding performance. *J. Mater. Sci: Mater. Electron.* **37**, 60 (2026)
11. S. Acharya, S. Datar, Wideband (8–18 GHz) microwave absorption dominated electromagnetic interference (EMI) shielding composite using copper aluminum ferrite and reduced graphene oxide in polymer matrix. *J. Appl. Phys.* **128**(10), 104902 (2020)
12. Pasha, A., Khasim, S. & Manjunatha, S.O. Highly efficient EMI shielding applications of porous nickel–iron ferrite doped with yttrium nanocomposite thin films as a multifunctional

- material. *J Mater Sci: Mater Electron* **34**, 409 (2023). <https://doi.org/10.1007/s10854-023-09844-3>
13. X. Xiang, Z. Yang, G. Fang, Y. Tang, Y. Li, Y. Zhang, D.H. Kim, Liu. Tailoring tactics for optimizing microwave absorbing behaviors in ferrite materials. *Mater. Today Phys.* **36**, 101184 (2023)
 14. Alam, F., Das, B.C., Das, H. *et al.* Investigation on structural, magnetic, dielectric and transport properties of nickel cobalt zinc ferrite–barium zirconium manganese titanium multiferroic composites. *Discov Mater* **6**, 160 (2026). <https://doi.org/10.1007/s43939-026-00621-7>
 15. Sukirman E, Sarwanto Y, Ahda S, Taryana Y, Purwanto S. Multiband electromagnetic wave absorption study on nanocrystalline (1–x) NiFe₂O₄/(x)BaTiO₃ Composites. *J Phys Conference Series*. 2020; 1436:012105.
 16. B. Du, M. Cai, X. Wang, Enhanced electromagnetic wave absorption property of binary ZnO/NiCo₂O₄ composites. *J. Adv. Ceram.* **10**, 832–842 (2021)
 17. Zeshan Munir , Muhammad , Nasir Amin , Iqra , Maria Akhtar ,Optimized EMI shielding effectiveness of Co-Cu-Gd spinel ferrites reinforced with graphene nanoplatelets, *Ceramics International* **52**, Issue **15**, Part **B**, 2026, PP 29338-29348, <https://doi.org/10.1016/j.ceramint.2026.05.013>
 18. Somnath Sahu, Ravi Chandra Gurralla, Pamu Dobbidi, Effect of rare earth substitution on electromagnetic and microwave absorption properties of nickel-cobalt nano ferrite, *Ceramics International*, **49**, Issue **24**, Part **A**, **15** (2023), Pages 40875-40893, <https://doi.org/10.1016/j.ceramint.2023.10.073>
 19. Isha S. Kapte , Sucharita Niyogi , Parvez J. Qureshi , Vaishnavi Khade , T. Avanish Babu , K.V. Siva kumar , W. Madhuri, Microwave assisted cobalt nickel ferrite as exhaust thrust sensor and EMI shield, *Ceramics International*, **50**, Issue **17**, Part **B**, **1** (2024), Pages 30754-30762, <https://doi.org/10.1016/j.ceramint.2024.05.376>
 20. Apsar Pasha ,Syed Khasim, A.A.A. Darwishb, Taymour A. Hamdalla, S. A. Al-Ghamdi, S. Alfadhli, Flexible, stretchable and electrically conductive PDMS decorated with polypyrrole/manganese-iron oxide nanocomposite as a multifunctional material for high performance EMI shielding applications, *Synthetic Metals*, **283**, 116984, [10.1016/j.synthmet.2021.116984](https://doi.org/10.1016/j.synthmet.2021.116984)
 21. Alsabab, Y.A., Abdulkarem, A.M., Alsuqia, I. *et al.* Structural, optical, and morphological characterization of Cd_xCo_{1-x}Fe₂O₄ spinel ferrite nanoparticles synthesized via the co-precipitation method. *Discover Nano* **21**, 332 (2026). <https://doi.org/10.1186/s11671-026-04774-5>
 22. Sulnata Z, Hossain M, Shil S, Rashid R, Khan M, Sikder S. Microstructure and magnetization process due To Cd²⁺ doped Ni-mg spinel ferrites. *Bangladesh J Phys.* 2021;28(2):51–8.
 23. Andhare, D.D., Patade, S.R., Jadhav, S.A. *et al.* Rietveld refined structural, morphological, Raman and magnetic investigations of superparamagnetic Zn–Co nanospinel ferrites prepared by cost-effective co-precipitation route. *Appl. Phys. A* **127**, 480 (2021). <https://doi.org/10.1007/s00339-021-04603-9>
 24. Boda N, Naidu K, Batoo K, Joice G, Naik J, Ravinder D. Structural, morphological and electronic properties of cadmium cobalt ferrite nanoparticles. *Biointerface Res Appl Chem.* 2020;10(1):4752–63.
 25. Sandeep B. Somvanshi, Mangesh V. Khedkar, Prashant B. Kharat, K.M. Jadhav, Influential diamagnetic magnesium (Mg²⁺) ion substitution in nano-spinel zinc ferrite (ZnFe₂O₄): Thermal, structural, spectral, optical and physisorption analysis, *Ceramics International*, **46**,7, 2020, pp

- 8640-8650,
<https://doi.org/10.1016/j.ceramint.2019.12.097>
26. Aridi, A., Rabaa, M., Moussa, R. *et al.* Influence of Gd³⁺ ion doping on structural, optical, and magnetic properties of (Mg–Ni–Co) nanoferrites. *J Nanopart Res* **25**, 228 (2023). <https://doi.org/10.1007/s11051-023-05879-z>
 27. M. Shruthi , Naveena Gadwala , A. Sridhar , D. Balaganesh , M. Prasad , Structural, magnetic, dielectric and visible-light emission properties of Gd³⁺-doped Ni–Mg spinel ferrites for high-frequency and optoelectronic applications, *Next Materials*, **13**, 2026, 103113, <https://doi.org/10.1016/j.nxmte.2026.103113>
 28. Shital P. Nawale , Punam B. Dube , Subhash M. Wani , A.P. Keche , K.M. Jadhav, Gd-doped Ni–Zn spinel ferrite nanoparticles via *piper nigrum*-mediated synthesis: Structural, optical, magnetic, and antibacterial properties, Article: 116489, Volume 416, 10.1016/j.ssc.2026.116489
 29. Muhammad Shahid , Sidra Shafi , Mohamed F. Aly , F. Aly , About , Muhammad Farooq Warsi , Impacts of Co²⁺ and Gd³⁺ co-doping on structural, dielectric and magnetic properties of MnFe₂O₄ nanoparticles synthesized via micro-emulsion route, *Ceramics International*, **43**, Issue 16, 2017, PP 14096-14100, <https://doi.org/10.1016/j.ceramint.2017.07.146>
 30. M. Asif Iqbal , Misbah-ul Islam , Muhammad Naeem Ashiq , Aisha Iftikhar , Hasan M. Khan , Effect of Gd-substitution on physical and magnetic properties of Li_{1.2}Mg_{0.4}Gd_xFe_(2-x)O₄ ferrites, *Journal of Alloys and Compounds*, **579**, 5 2013, Pages 181-186, <https://doi.org/10.1016/j.jallcom.2013.06.033>
 31. P.R. Koushalya , S.O. Manjunatha , B.S. Prathibha , Apsar Pasha , Fabrication of highly conductive PEDOT:PSS/CdFe₂O₄ composite thin films-based sensors towards detection of greenhouse methane gas at ppb level. *Synthetic Metals* **320** (2026) 118213. DOI: 10.1016/j.synthmet.2026.118213
 32. Apparao R. Chavan , Shankar D. Birajdar , Rahul. Structural, morphological, optical, magnetic and electrical properties of Al³⁺ substituted nickel ferrite thin films, *Journal of Alloys and Compounds*, **735**, 25 2018, PP 2287-2297, <https://doi.org/10.1016/j.jallcom.2017.11.326>
 33. Shakir, M.F., Tariq, A., Rehan, Z.A. *et al.* Effect of Nickel-spinal-Ferrites on EMI shielding properties of polystyrene/polyaniline blend. *SN Appl. Sci.* **2**, 706 (2020). <https://doi.org/10.1007/s42452-020-2535-4>
 34. Sahin, E.İ., Ibrahim, J.E.F.M., Emek, M. *et al.* Structural and shielding effectiveness properties of (NiFe₂O₄/chopped strands) composites for 6.5–18 GHz applications. *J Mater Sci: Mater Electron* **35**, 1407 (2024). <https://doi.org/10.1007/s10854-024-12965-y>
 35. Apsar Pasha, Syed Khasim, Improved broad band electromagnetic interference shielding and strain sensing properties of multifunctional reduced Graphene Oxide/Iron-Cobalt ferrite composites. *Journal of Electronic Materials: Materials in Electronics*: **35**, 48 (2024). <https://doi.org/10.1007/s10854-023-11781-0>
 36. D. Mondal , D. Bhattacharya , T. Mondal , M. Kundu , S. Sarkar , T.K. Mandal , B.K. Paul , S. Das , Rare earth ion-infused α-MnO₂ nano-rods for excellent EMI shielding efficiency: Experimental and theoretical insights, *Sustainable Materials and Technologies*, **38**, 2023, e00772, <https://doi.org/10.1016/j.susmat.2023.e00772>

37. Ismail, M.M., Rafeeq, S.N., Sulaiman, J.M.A. *et al.* Electromagnetic interference shielding and microwave absorption properties of cobalt ferrite CoFe_2O_4 /polyaniline composite. *Appl. Phys. A* **124**, 380 (2018). <https://doi.org/10.1007/s00339-018-1808-x>
38. Wang, F., Wang, X., Zhu, J. *et al.* Lightweight NiFe_2O_4 with controllable 3D network structure and enhanced microwave absorbing properties. *Sci Rep* **6**, 37892 (2016). <https://doi.org/10.1038/srep37892>
39. Khalid Mujasam Batoo, Ankush Chauhan, Ritesh Verma, Mahavir Singh, Omar M. Aldossary, Gagan Kumar Bhargava, High-frequency applications of bismuth-doped Co–Zn ferrite nanoparticles for electromagnetic interference filter and multilayer inductor chip fabrication, *Applied Physics A* (2022) 128:283 <https://doi.org/10.1007/s00339-022-05423-1>
40. K. Pubby, S. Meena, S. Yusuf, S.B. Narang, Cobalt substituted nickel ferrites via Pechini's sol-gel citrate route: X-band electro-magnetic characterization. *J. Magn. Magn. Mater.* **466**, 430–445 (2018)
41. Bera, P., Lakshmi, R.V., Chakradhar, R.P.S. *et al.* Electromagnetic interference shielding properties of PMMA modified- $\text{Co}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ – polyaniline composites. *Functional Composite Mater* **5**, 11 (2024). <https://doi.org/10.1186/s42252-024-00059-1>
42. Lee, H., Ryu, S.H., Kwon, S.J. *et al.* Absorption-Dominant mmWave EMI Shielding Films with Ultralow Reflection using Ferromagnetic Resonance Frequency Tunable M-Type Ferrites. *Nano-Micro Lett.* **15**, 76 (2023). <https://doi.org/10.1007/s40820-023-01058-w>
43. Numrah Sultan, Khaqan Shati, Ubaid Ur Rehman, M. Nadeem, Polyaniline-encapsulated carbon-coated nickel zinc ferrite: A hybrid composite for enhanced absorption-dominant EMI shielding, *Synthetic Metals*, **Article**: 117883, [10.1016/j.synthmet.2025.117883](https://doi.org/10.1016/j.synthmet.2025.117883)
44. Vaishnavi Khade;, Avanish Babu Thirumalasetty, Asmita Ajay Rathod; Yogesh Kumar Chaoukiker; Flexible and rigid spinel ferrite carboneous composite as a future of tunable absorption dominant cmWave shielding materials, *J. Mater. Chem. A* (2024) 12 (15): 8914–8926. <https://doi.org/10.1039/d3ta07624e>
45. Sahin, E.İ., Ibrahim, J.E.F.M., Emek, M. *et al.* Structural and shielding effectiveness properties of (NiFe_2O_4 /chopped strands) composites for 6.5–18 GHz applications. *J Mater Sci: Mater Electron* **35**, 1407 (2024). <https://doi.org/10.1007/s10854-024-12965-y>
46. Raghvendra Singh Yadav, Ivo Kuřitka, Jarmila Vilcakova, Masař, Lightweight NiFe_2O_4 -Reduced Graphene Oxide-Elastomer Nanocomposite flexible sheet for electromagnetic interference shielding application, *Composites Part B: Engineering*, Volume 166, 1 2019, Pages 95-111, <https://doi.org/10.1016/j.compositesb.2018.11.069>
47. R.S. Yadav, I. Kuřitka, Spinel ferrite and MXene-based magnetic novel nanocomposites : an innovative high-performance electromagnetic interference shielding and microwave absorber, *Crit. Rev. Solid State Mater. Sci.* **48** (2023) 441–479, <https://doi.org/10.1080/10408436.2022.2067122>
48. M.M. Anju, A. Machovsk, Michal Urb'eanek, a Pavol ěsuly, J.V. Barbora Hanulıkov, I. Kuritka, R.S.Y. Ab, Optimization of CoFe_2O_4 nanoparticles and graphite fillers to endow thermoplastic polyurethane nanocomposites with superior electromagnetic interference shielding performance, 2149–2165, <https://doi.org/10.1039/d3na01053h>, 2024.