

Microwave absorption performance of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters at 8.2–18 GHz frequency

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Abstract: The evolution of nanomaterials has significantly contributed to the advancement of smart and lightweight electromagnetic (EM) wave absorbing materials. In this study, $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters were synthesized by a facile co-precipitation route. The morphology, structure, phase, and chemical composition of the sample was investigated. Results show that the sample is composed of clustered $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoparticles, wherein the nanoparticles clusters are composed of tiny individual particles with spherical morphology. Investigation of the EM wave absorption reveals that a composite of paraffin containing 20 wt% of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters absorbs a large percentage of the incident EM wave at a thin absorber thickness. The sample attains – 48.8 dB reflection loss at 14.42 GHz with a 3.0 mm thickness. The enhanced EM absorption performance can be ascribed to interface polarization resulting from the many active atoms on the surface of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters. These results show that the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters can be used to effectively attenuate microwaves.

Keywords: Electromagnetic wave; Microwave absorbing material; $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$; Nanoclusters; Reflection loss

1. Introduction

Recent advances in electromagnetic (EM) wave applications have resulted in an environmental menace termed EM pollution. EM radiation from different power sources is utilized in various applications including wireless communications and advanced military equipment such as radar technology and navigation systems, mining, tunnelling, and mineral processing [1–3]. These exhaustive use of EM wave applications have resulted in adverse health effects on humans [4, 5]. In the electronic industry, EM interference (EMI) is a disturbance that affects an electrical circuit of a device due to EM radiation from a

nearby EM power source [6]. EMI has been recognized as another serious problem resulting in decrease of precise equipment efficiency [7]. Therefore, the need for shielding from EM pollution and safeguarding electronic devices from EMI has become important. Hence, materials that can absorb EM wave by dissipating the EM wave loss have been widely put forward as an effective solution to these problems. EM wave absorption process involves the loss of EM energy, wherein the EM energy is dissipated within the absorptive materials and may be converted to other energy forms like heat.

In this regard, traditional EM wave shielding materials mostly metals such as aluminium, silver, manganese, and ferrites have been studied for EM waves absorption [8]. However, the bulk form of these materials presents some disadvantages such as heaviness, bulkiness, and high corrosion tendency which impede their practical application.

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Another major issue with these materials is their high conductivity which often results in large reflection of EM wave rather than the desired absorption. Specifically, the high electron mobility at their near-surface lead to significant skin effect on the radiated EM wave [9]. The skin effect can be explained as the depth of propagation of EM wave where the initial wave amplitude reduces to $1/e$ (37%). Nanomaterial with sizes less than the dimension of the skin depth have been widely put forward as a potential replacement for the bulk materials [3, 10]. Also, nanomaterials have good magnetic and electric properties because of their surface structure, small size, and possible quantum effect. Besides, their relative density is lower, hence their higher specific surface area as against the corresponding bulk form. Thus, there exist a huge number of active atoms and increased polarization sites on the surface of nanomaterials, which would yield enough interfacial polarization [11, 12].

In this study, $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters were synthesized via co-precipitation route, with subsequent calcination at high temperature. The structural property of the sample was studied using XRD and FTIR as well as TEM. While the morphology of the sample was investigated using FESEM. Results from the investigation of the EM wave absorption performance reveal that 20 wt% of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters can effectively absorb EM wave.

2. Experimental

2.1. Methodology

Analytical grade nickel(II) nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), zinc (II) nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), iron (III) nitrate nonahydrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) and sodium hydroxide (NaOH) precursors purchased from R & M chemicals were used as the starting material. NiZn ferrite nanoparticle was synthesized via a conventional chemical co-precipitation route. The starting materials $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, and $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ with a proportional ratio of 4:1:1 were mixed in deionized (DI) water (150 mL) and magnetically stirred for 30 min at 80 °C. The NaOH (15 mL) was subsequently added dropwise into the solution while maintaining the temperature at 80 °C. The solution was stirred continuously for 4 h at 80 °C and subsequently aged for 5 h in ambient condition. The obtained product was then washed severally with DI water drying at 75 °C in an oven. The dried powder sample was calcined in air at 750 °C for 2 h at 5 °C/min ramping rate.

2.2. Characterization

Crystalline structure and phase composition of the synthesized $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters were investigated by X-ray diffractometer (XRD, Malvern Panalytical, Malvern, UK) with $\text{Cu K}\alpha$ radiation ($\lambda = 0.15406$ nm, 40 mA and 45 kV). Agilent Cary s630 Fourier transform infrared spectroscopy (FTIR) spectrometer was utilized to investigate the presence of specific chemical groups in the IR spectra of the samples in 650–4000 cm^{-1} wavenumber range. Magnetic hysteresis curve of the material was measured by a vibrating sample magnetometer (VSM 648 series, Lakeshore, Westerville, OH, USA). The X-ray photoelectron spectroscopy (XPS) analysis carried out on Thermo scientific K-alpha X-ray photoelectron spectrometer was used to establish the valency state of the ions present on the nanoparticles' surfaces. The samples stoichiometry was determined from all survey scans. Transmission electron microscopy (TEM) was implemented with a JEOL JEM 2010F at 200 kV to study the structural properties. The sample morphology was examined by Field emission scanning electron microscopy using FESEM Carl Zeiss, model SUPRA 55 VP AG, Germany. For EM properties measurements, the sample was filled in paraffin at 10 wt% and 20 wt% labelled as NZC@10 and NZC@20 respectively. The EM parameters (μ and ϵ) of the samples were measured within 8.2–18 GHz frequency range, via vector network analyzer (Keysight E5071C, USA).

3. Results and discussion

The XRD pattern of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanocluster is presented in Fig. 1, where the prominent 2θ diffraction

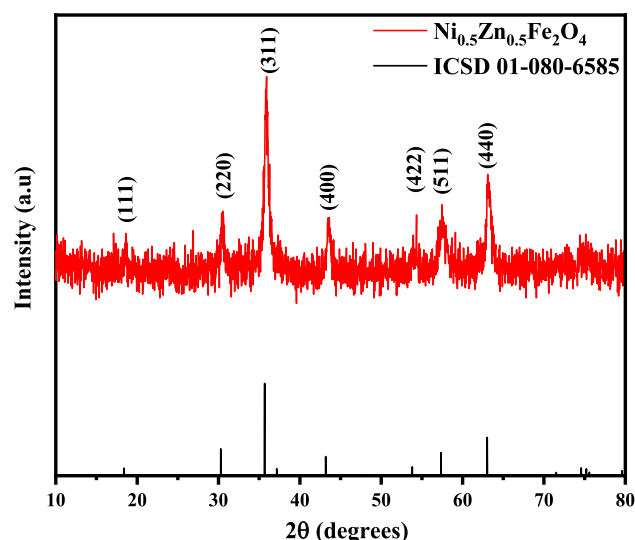


Fig. 1 XRD pattern of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters

peaks occur at diffraction angles 18.32, 30.11, 35.46, 43.07, 53.46, 56.98 and 62.54 are assigned to their crystalline planes (111), (220), (311), (400), (422), (511) and (440), respectively according to ICSD crystallographic database (card no. 01-080-6585). This confirms the cubic spinel structure of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoparticles. The sample's crystallite size was calculated as 13.8 nm using the Debye–Scherrer equation $D = \frac{0.9\lambda}{\beta \cos \theta}$ [13], where λ represents the X-ray radiation wavelength, β is the broadening at half maximum intensity (FWHM), and θ is the Bragg's angle.

The morphological features of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters observed via FESEM analysis are presented in Fig. 2. It is observed from the low magnification image (Fig. 2(a)) that the samples are homogeneously distributed. The high magnification FESEM micrograph (Fig. 2(b)) shows that the sample is composed of clustered nanoparticles. The clusters of nanoparticles are composed of tiny individual particles with spherical morphology. The clustered particles due to agglomeration of individual crystallites is due to some emerging forces at high calcination temperature. These forces include the emergence of magnetic moments that are proportional to the particles volume, emergence of Van-der Waals, electrostatic, and capillary forces. The observed particle size in the FESEM

micrograph is significantly larger than that calculated from the XRD pattern. This is because the XRD calculation is based on a single crystallite, while the observed FESEM particles are composed of multiple crystallites [14]. The sample elemental composition was investigated via energy dispersive X-ray analysis (EDX). Electron image of the scanned sample surface and the EDX spectrum are presented in Fig. 2(c) and (d) respectively. The presence of Zn, Ni, Fe and O peaks in the EDX spectrum confirms the formation of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoparticles, while the lack of other peaks indicates the purity of the sample.

TEM analysis of the sample was conducted for further morphological and crystallinity investigations, the results are displayed in Fig. 3. The sample is composed of spheroidal grains that are homogeneously distributed in clusters (Fig. 3(a) and (b)). Most of the particles are agglomerated as primary particles, with no visible grain boundaries, nevertheless, there are few observable individual crystallites. A large portion of the individual crystallites spontaneously assembled into clusters to achieve a lower free energy state during synthesis. This leads to a reduction of interface from one particle to the other, consequently resulting in low surface area [15, 16]. Figure 3(c) shows the magnified image of a cluster in the sample, where the inset is the corresponding selected area

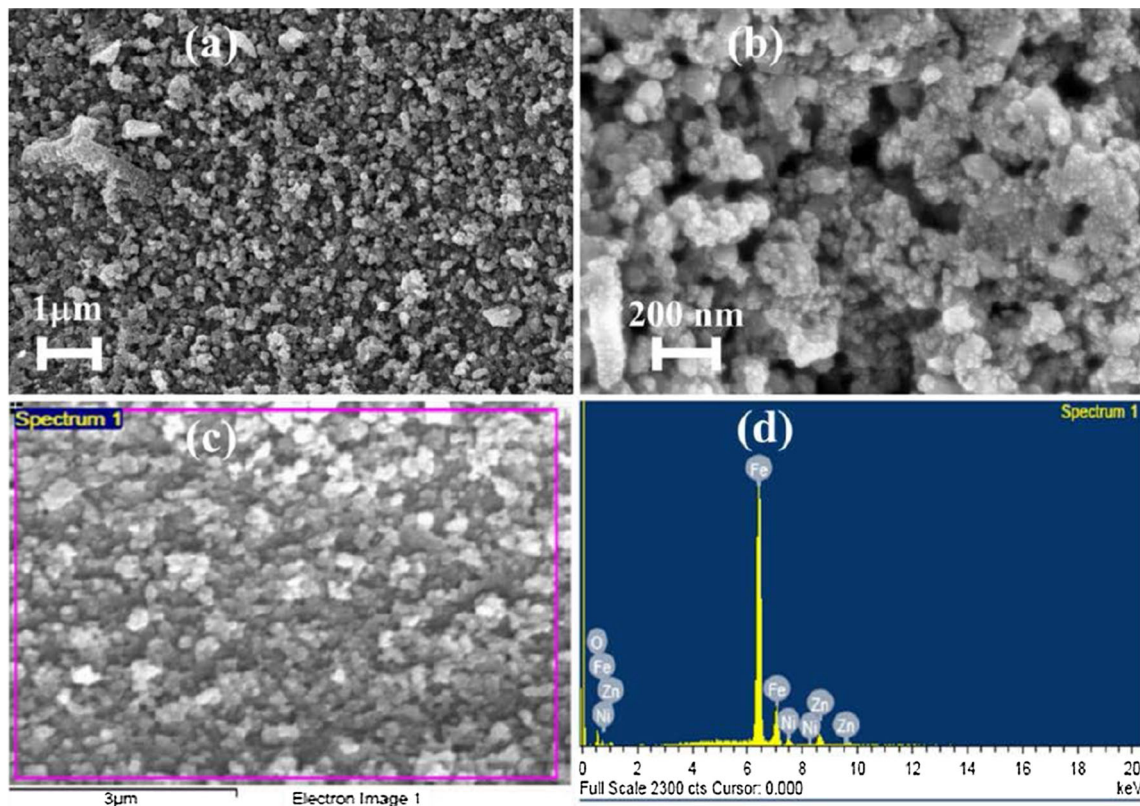


Fig. 2 FESEM images of c (a) at low magnification, (b) at high magnification showing the clustered particles, (c) EDX electron image (d) EDX spectra showing the elemental composition

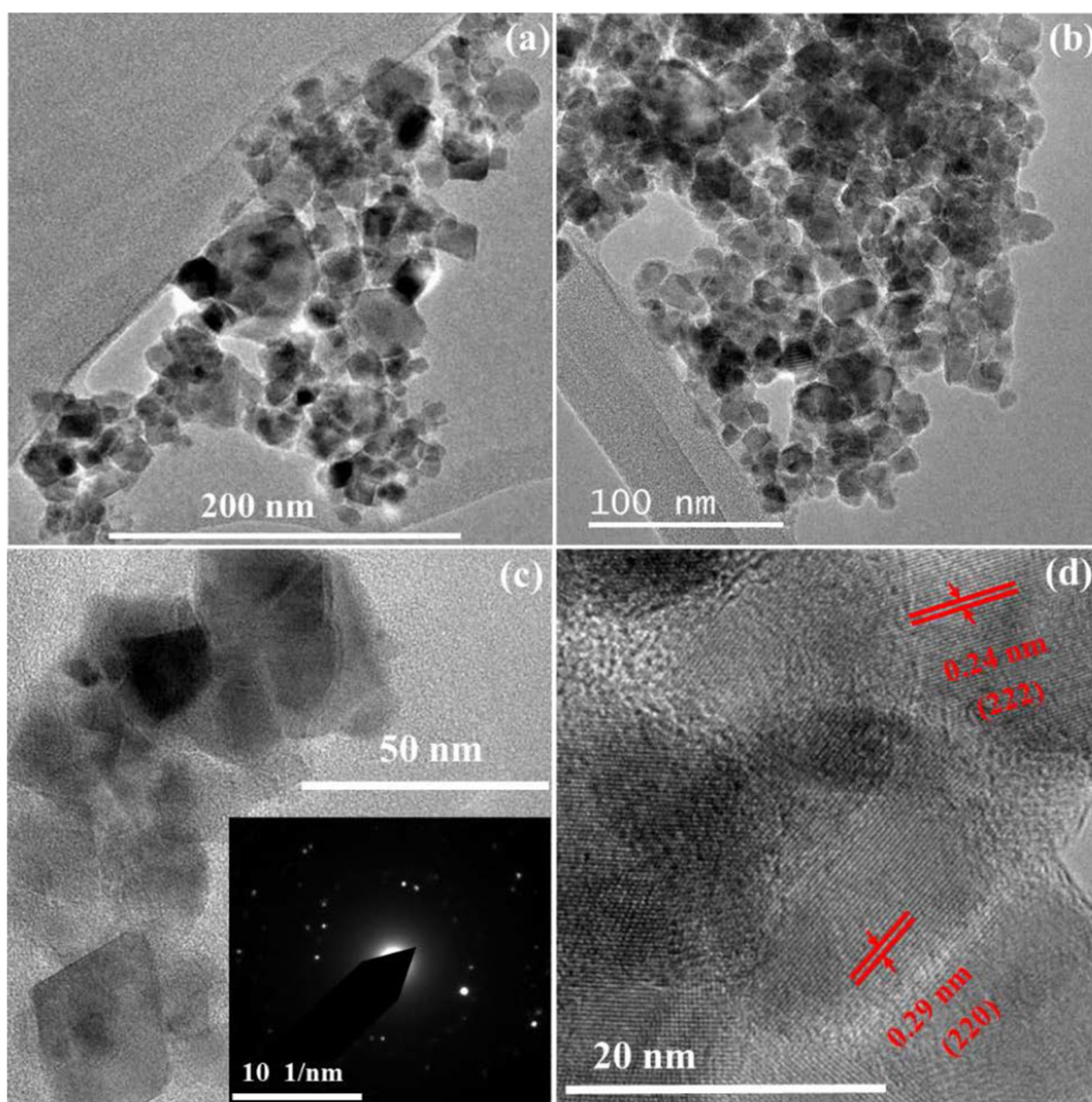


Fig. 3 (a)–(c) HRTEM micrograph of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters at low and high magnifications, respectively. The inset in (c) shows SAED pattern, and (d) shows lattice interplanar spacing

electron diffraction (SAED). The bright spots in the SAED tend to overlap along the ring. This indicates that the sample is polycrystalline. Figure 3(d) further shows the crystalline structure of the sample. Some lattice fringes with lattice spacing 0.29 nm and 0.24 nm are observed. These lattices spacing correspond to the (220) and (222) crystal planes (of the XRD pattern) of the spinel $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ respectively.

The TG-DTA analysis of the synthesized $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters measured in air is shown in Fig. 4(a). From the inspection of the TG-DTA curve characteristics, the thermal decomposition process of the sample can be grouped into three steps. The first weight loss, which is equivalent to the loss of crystalline water, occurs around 100 °C. This amounts to approximately 3.7% loss in total

weight. The second weight loss between 100 and 390 °C accounts for the decomposition of residual precursors (metal nitrates). The observed exothermic peak covering the second and third weight losses (around 400 °C) could be due to oxidation of Fe^{2+} to Fe^{3+} as illustrated in the Eq. (1) [17].



where M represents transmission metal element (Ni–Zn), and Q_T is the accompanying mass increase indicated by the DTA curve at the corresponding temperature T (200–650 °C). Finally, in the temperature range 400–700 °C the individual tiny solid-state reaction yields $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters after decomposition. The infrared spectra of the sample were obtained via FT-IR

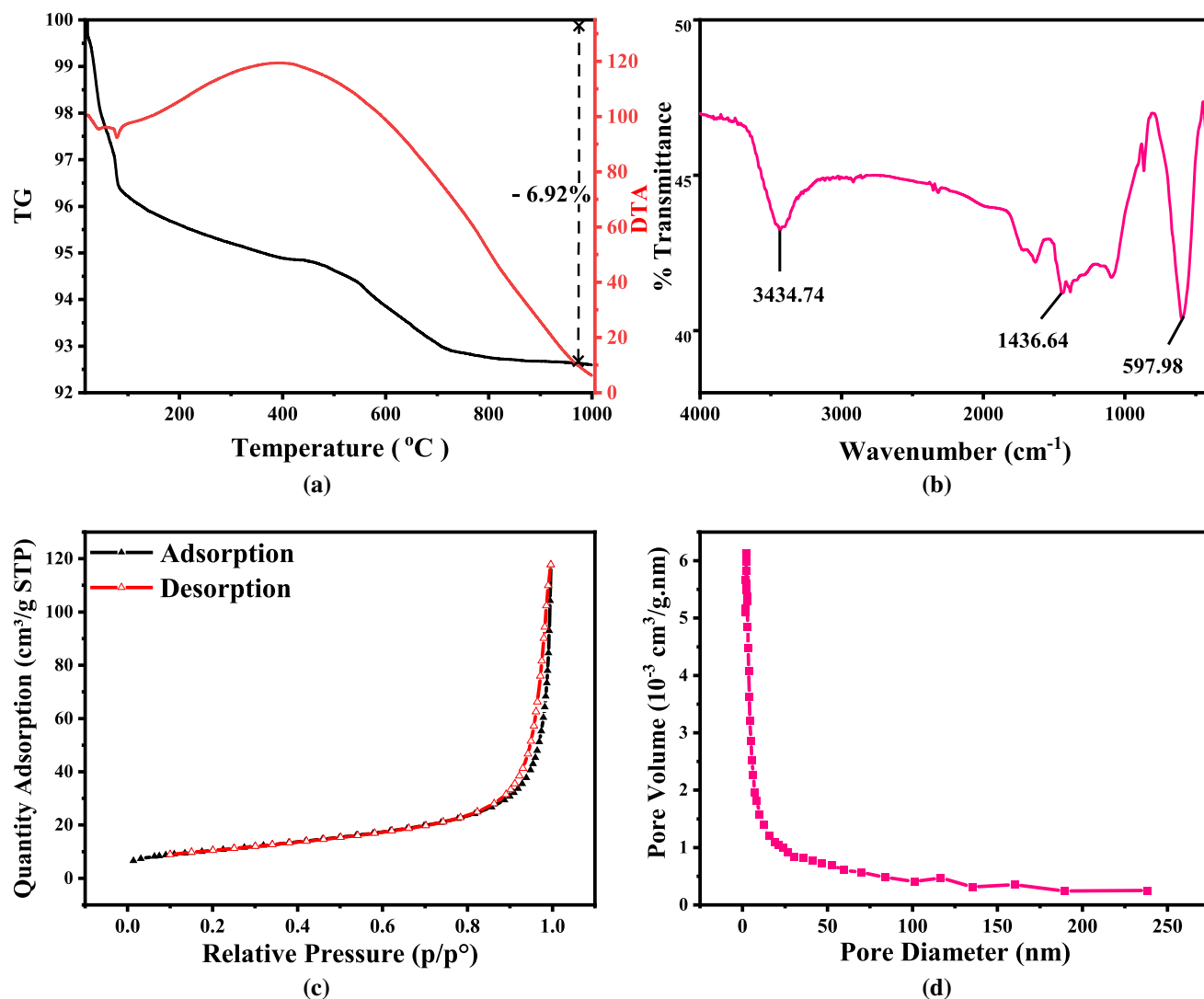


Fig. 4 (a) TG-DTA curve, (b) IR spectra, (c) BET N_2 adsorption/desorption isotherm, and (d) BJH pore size distribution of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters

spectroscopy within 400–4000 cm^{-1} wavenumber. The obtained curve is presented in Fig. 4(b). The single strong absorption peak around 597 cm^{-1} is a characteristic vibration of metal oxides. This peak emanates from the stretching and winding vibration of the Fe–O, Ni–O, and Zn–O in the tetrahedral site [18, 19]. The weak stretching absorption peak at 1436 cm^{-1} could be a result of the residual nitrates of the precursors. While the absorption peak at 3434.74 cm^{-1} indicates the presence of an OH group in the sample.

To identify the porosity and pore structure of the sample, the samples were degassed at 100 °C for 12 h for moisture removal. Subsequently, N_2 adsorption/desorption isotherms analysis was conducted on the sample. The specific surface area and pore volume distribution based on Barrett–Joyner–Halenda (BJH) and Barrett–Emmett–Teller (BET) methods are displayed in Fig. 4(c) and

(d) respectively. A steady increase in adsorption quantity is observed within P/P_0 value of 0.1–0.8 (Fig. 4(c)). The curve then becomes steep within 0.8–1.0 vicinity, thereby displaying a class IV curve [17]. The desorption part is generally above its adsorption counterpart, however, but becomes parallel in the saturated vapour pressure region. The adsorption/desorption isotherm hence displays an H3 characteristic hysteresis loop [20]. Based on the BJH calculation method, the sample is composed of mesopores, which has pore sizes of 15–25 nm (Fig. 4(d)). The BJH adsorption cumulative surface area of pore sizes within 1.7–300 nm diameter is 36.27 m^2g^{-1} , while the BET surface area is 36.39 m^2g^{-1} . These are benign features, which could lead to a reduction of the sample density and EM wave absorption enhancement due to trapping and multiple internal reflections of incident EM wave within the pores [17].

The valency and presence of Fe, Ni, Zn, and O in the synthesized sample were confirmed from XPS spectra. A collection of the high-resolution photoemission of the survey, and the deconvoluted Zn, Fe, Ni, and O signals are presented in Fig. 5(a)–(e). The presence of Me^+ ion structure in the material is established by the Ni $2p_{3/2}$ and Zn $2p_{3/2}$ binding energies [21]. The Zn $2p$ cores were split into $2p_{2/3}$ and $2p_{1/2}$ (Fig. 5(b)). Symmetric $2p_{1/2}$ and $2p_{2/3}$ main peaks with binding energies at 1045.03 eV and 1021.85 eV respectively characterize the Zn state, with absence of satellites. The Fe $2p$ spectrum presented in Fig. 5(c) shows the main contributions of two components: Fe $2p_{3/2}$ and Fe $2p_{1/2}$ with binding energies 716.08 eV and 729.29 eV. Also, there are presence of corresponding satellite peaks at 720 eV and approximately 735 eV. Hence, the Fe in the sample occurs in a $2 + 3 +$ mixed-valence state, which conforms to ferrite structures [22–24]. Similar peak allocation and assignments made for the Ni $2p$ signal (Fig. 5(d)) indicate that Ni is mainly in the Ni^{2+} and Ni^{3+} states. This is evidenced by the strong shakeup satellite arising from the unpaired 3d orbitals electron of the high spin energy of Ni^{2+} [25]. The O $1s$ peak (Fig. 5(e)) with major binding energy 536.42 eV and a less intense peak at 542.25 eV further supports the

formation of the ferrite structure [26]. Figure 5(f) displays the sample's Raman spectrum with three distinct modes at 482, 569, and 701 cm^{-1} . These peaks coincide with the $A_{1g} + E_g + 3F_{2g}$ Raman modes of the spinel structures [27]. The A_{1g} mode at 701.6 cm^{-1} is associated with stretching vibration of the O atoms in proximity of the Fe–O tetrahedral bond, whereas the 569.4 cm^{-1} mode belongs to oxygen atoms asymmetric bending vibration in the octahedral sites. The mode positioned at 482.7 cm^{-1} has $F_{2g}(2)$ symmetry and is linked to the Fe–O, Zn–O, and Ni–O asymmetric vibration in octahedral sites of the spinel structure [28].

The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters room temperature magnetic properties were investigated by a VSM. The measured M – H hysteresis loop is shown in Fig. 6. The sample exhibits a typical soft superparamagnetic behaviour evidenced by the narrow hysteresis curve, with saturation magnetization (M_s) value of 18.5 emu g^{-1} . A magnified image of the low field hysteresis curve is shown in the inset, having coercivity (H_c) value of 82.15 G, and remnant magnetization (M_r) of 0.89 emu g^{-1} . The M_s , M_r , and H_c of the sample are limited by the small individual crystallite size of the sample, which yields increased spin suspension bonds, resulting in reduced net spin moment

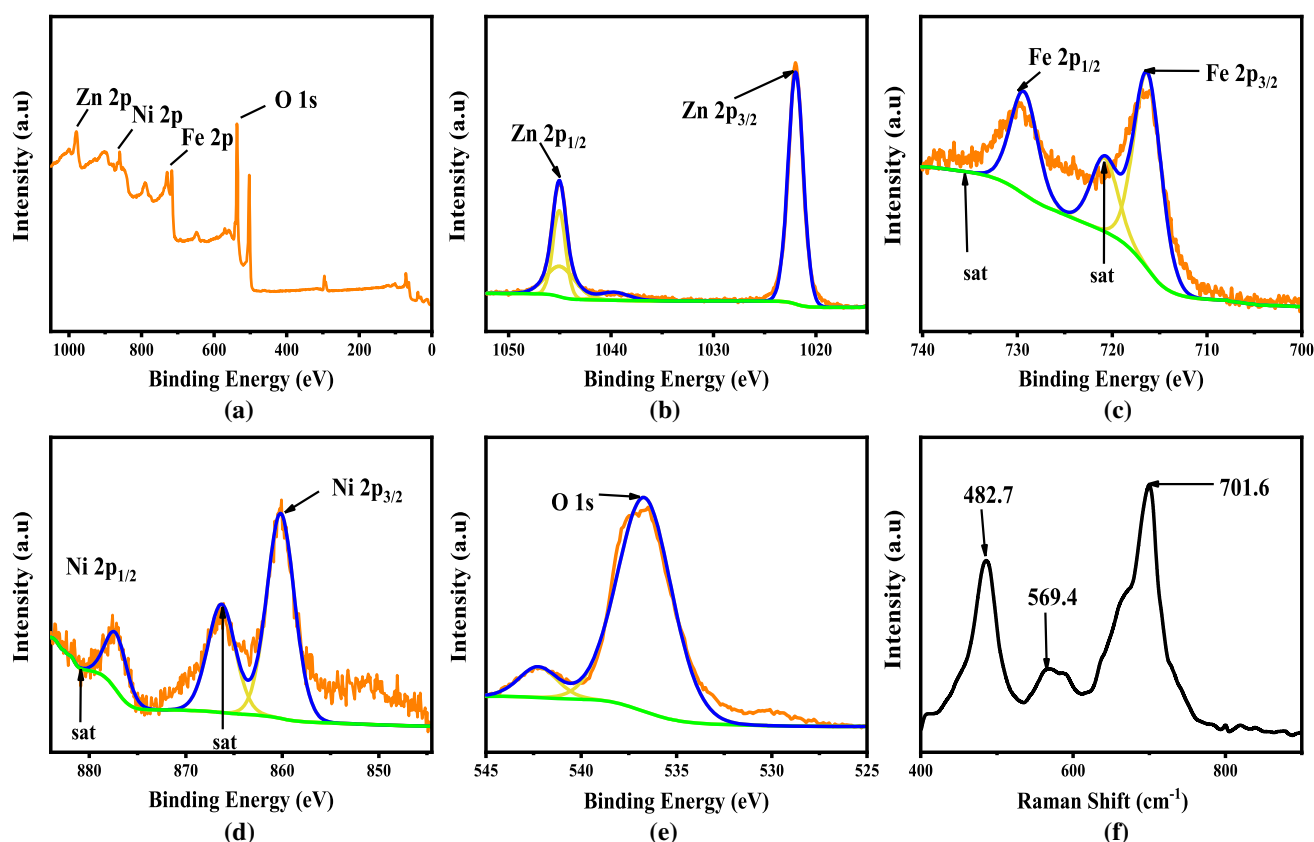


Fig. 5 XPS spectra; (a) survey spectrum, (b) Zn $2p$, (c) Fe $2p$, (d) Ni $2p$, and (e) O $1s$ spectra. (f) Raman spectrum of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters

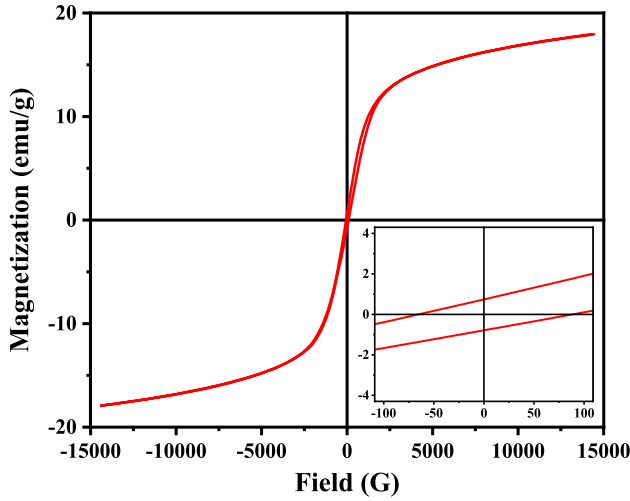


Fig. 6 Hysteresis curve of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters. The inset shows magnified low field hysteresis

[17]. The low coercive force suggests that crystallite size is smaller than the critical grain size within the domain wall [29]. The observed low coercive force can benefit EM wave absorption performance of the sample, as small H_c values are known to aid magnetic and electric coupling [30].

The microwave absorption performance of the material was studied in relations to the complex permeability ($\mu' - j\mu''$) and permittivity ($\epsilon' - j\epsilon''$). With the real (ϵ' and μ') and imaginary (ϵ'' and μ'') parts representing EM wave energy storage and dissipation ability of the material [10, 31]. The permeability and permittivity of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ samples are presented in Fig. 7. The numerous fluctuations observed in both ϵ' and ϵ'' may be attributed to polarization mechanisms such as the interfacial polarization between the NiZn ferrite and paraffin wax, as well as surface charge

polarization. The characteristic dielectric decrease with increasing frequency is also observed in all both samples (Fig. 7a). This behaviour has been reported to be supported by the high effectiveness of grains over grain boundary at higher frequency which results in lower permittivity at higher frequency and vice versa [32–34]. Nevertheless, the dielectric properties of the NZC@10 are significantly small, with ϵ' and ϵ'' in the range 2.6–4.1 and 0.26–0.96 respectively. This was however drastically increased with increase in the sample loading to 20 wt%. The ϵ' and ϵ'' values of the NZC@20 increased to 4.9–9.6 and 0.6–2.8 respectively. Figure 7b displays the permeability of the ferrimagnetic materials over a frequency range 8.2–18 GHz. Both μ' and μ'' generally decreases with increasing frequency with some noticeable peaks. The peaks in the μ'' plot within 2–14 GHz have been earlier reported to be associated with natural and exchange resonances, which is responsible for the magnetic loss capability of the material [4].

Figure 8(a) and (b) shows the dielectric ($\tan \delta_e = \epsilon''/\epsilon'$) and magnetic ($\tan \delta_\mu = \mu''/\mu'$) loss tangents, respectively. The $\tan \delta_e$ and $\tan \delta_\mu$ plots indicate that dielectric loss dominates the EM wave energy attenuation within the samples, although, magnetic loss mechanism also has a significant contribution. Generally, magnetic losses arise from either exchange resonance, eddy current loss, or natural resonance phenomena [10]. The magnetic loss source is investigated by the plot of $C_o \left(\mu''/(\mu')^2 f \right)$ against frequency. The magnetic loss is known to originate from eddy current loss if the C_o values stays constant with frequency increase, while exchange and natural ferromagnetic resonance dominates if C_o varies with frequency increase [35].

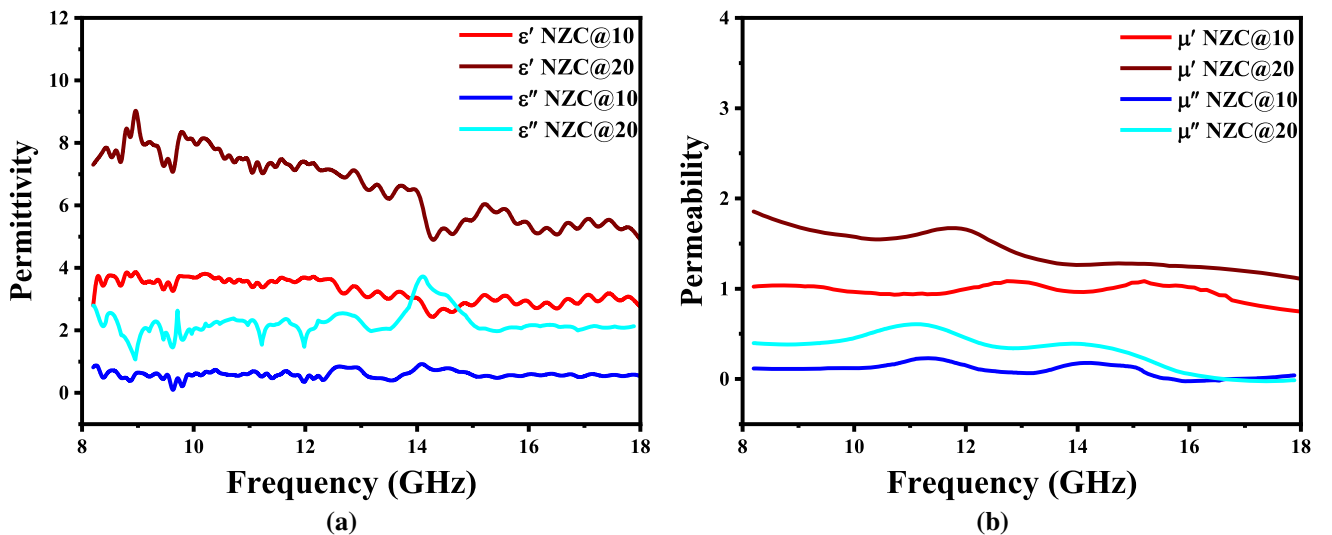


Fig. 7 (a) Permittivity and (b) permeability of the samples at 8.2–18 GHz

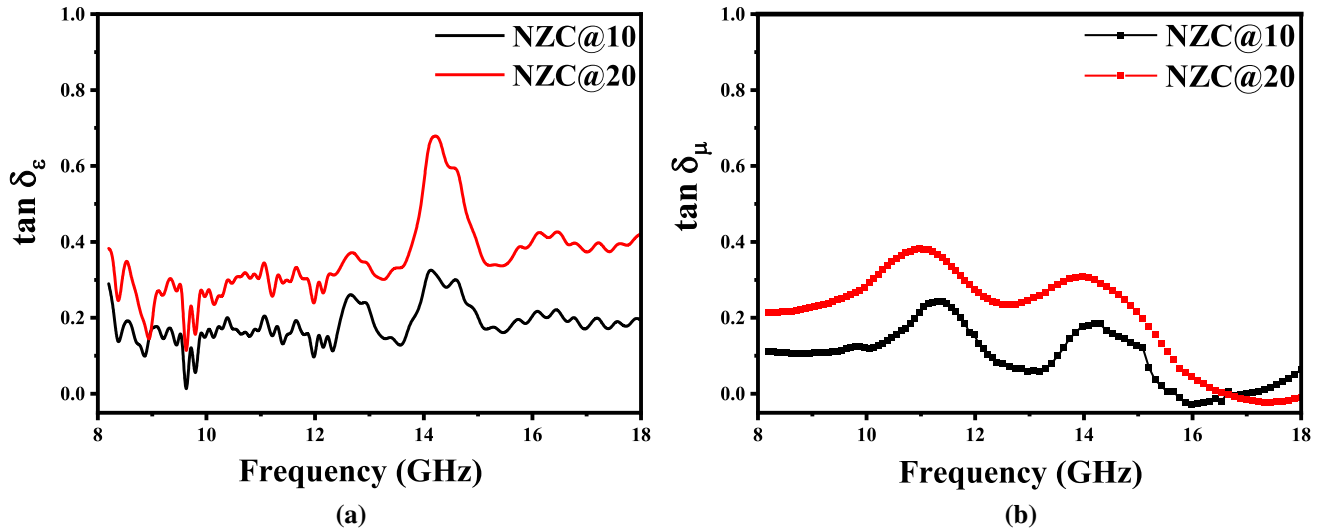


Fig. 8 (a) Dielectric and (b) magnetic loss tangents of the samples at 8.2–18 GHz

The C_o plot of the sample at 10 wt% and 20 wt% loading within a frequency range of 8.2–18 GHz are displayed in Fig. 9. The C_o curves of both samples vary significantly within 10–15 GHz frequency range, while remaining constant at other frequencies. This indicates that the magnetic loss of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters emerges from both exchange and natural ferromagnetic resonance, and eddy current loss [36]. The natural ferromagnetic resonance contribution of the magnetic loss is described by

$$f_R = \frac{\gamma H_a}{2\pi}, \quad \text{and} \quad H_a = \frac{4|K_1|}{3\mu_0 M_s}, \quad K_1 > 0$$

where f_R is the ferromagnetic resonance, γ is the gyro-magnetic ratio, H_a is the effective anisotropy field, K_1 is the anisotropy constant, μ_0 is the permeability of vacuum, and

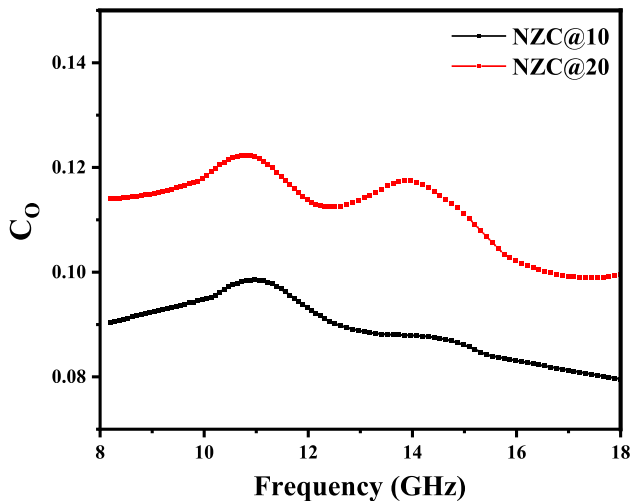


Fig. 9 Frequency-dependent of C_o values of the samples

M_s is the saturation magnetization [37]. The natural ferromagnetic resonance mechanism extends over a broad frequency range (approximately within 10–15 GHz) as indicated in the C_o plot. This broad resonance frequency range can contribute to the remarkable microwave absorption performance of the material.

The EM waves absorption performance of the material were investigated via reflection loss (RL). The RL values of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters were calculated based on the permeability and permittivity using the equations below

$$\text{RL(dB)} = 20 \log_{10} \left| \frac{Z_{\text{in}} - Z_o}{Z_{\text{in}} + Z_o} \right| \quad (2)$$

$$Z_{\text{in}} = Z_o \sqrt{\frac{\epsilon_r}{\mu_r}} \tanh \left(j \frac{2\pi f d}{c} \sqrt{\epsilon_r \mu_r} \right) \quad (3)$$

where Z_{in} is the input impedance of the absorbing material, Z_o is the characteristic impedance of free space, μ_r and ϵ_r are the relative permeability and permittivity respectively, c is the velocity of light, f is the EM wave frequency, d is the material thickness. RL values lesser than -10 dB are generally believed to correspond to 90% EM waves absorption by the absorbing material. The feasibility of practical applications of EM absorbers are based on this criterion. Three-dimensional representations of the frequency dependent RL curves frequency of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanocluster filled paraffin composites at 10 wt% and 20 wt% are presented in Fig. 10. Sample NZC@10 (Fig. 10a), displayed relatively poor EM wave absorption ability achieving a minimum RL value of -48.8 dB at 14.42 GHz with a large absorber thickness of 5.0 mm. The dissipation of EM wave by the sample greatly improved with NZC@20. Minimum RL values of -48.8 dB, -50.8 dB, -52.3 dB, -43.1 dB and -64.6 dB were

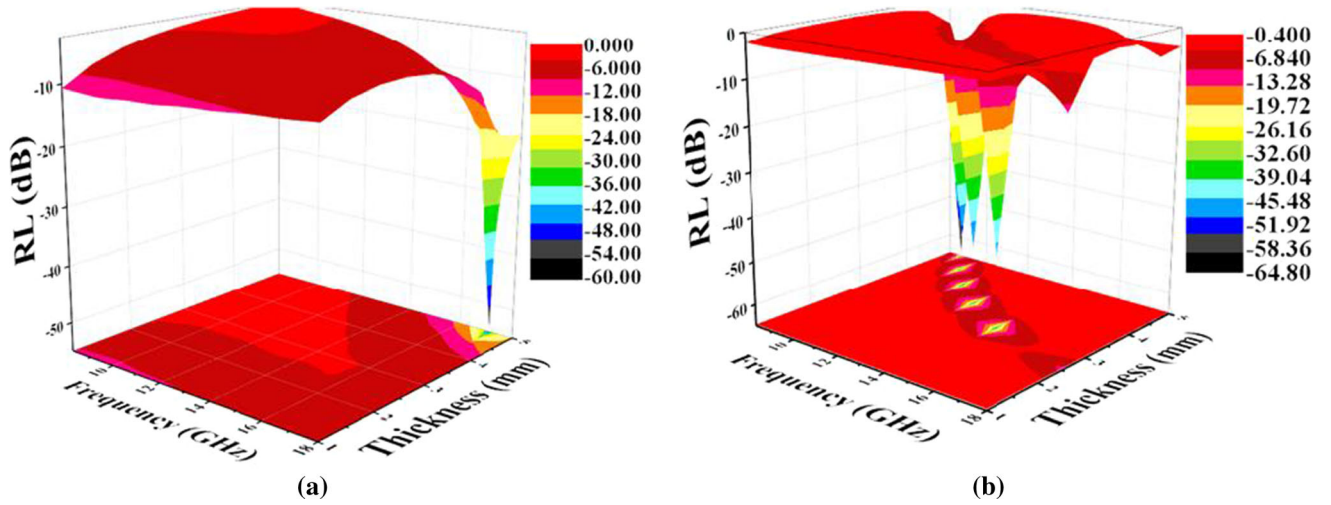


Fig. 10 Three-dimensional plot of frequency and thickness dependent RL at (a) 20 wt%, and (b) 10 wt% absorber weight loading

achieved at an absorber thickness of 3.0, 3.5, 4.0, 4.5, and 5.0 mm respectively, corresponding to 99.99% absorption of the EM waves [38, 39].

Plots of the frequency dependent RL curves of the sample at 10 and 20 wt% with thicknesses ranging from 2.0 to 5.5 mm are presented in Fig. 11. It has been established that the absorption performance of EM waves absorbing materials is associated with thickness. Figure 11a shows that the 10 wt% of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanocluster cannot satisfy the demand of an ideal absorbing materials with absorption at large thickness of 5 mm. Whereas, an increase in the filler loading to 20 wt% resulted in satisfying absorption performance. The absorption bandwidth can approach 7.8 GHz (8.2–16.0 GHz) by tuning the thickness from 3.0 to 5.0 mm (Fig. 11b). The EM wave absorption performance of the samples aligns with the quarter-wavelength regulation as the optimal absorption frequency drifts towards the lower frequency range as thickness increases [40]. This behaviour can be described with the quarter-wavelength model matching where the absorptive material thickness, t_m varies inversely with the matching frequency, f_m as and can be expressed as presented in Eq. (4).

$$t_m = n\lambda/4 = nc / \left(4f_m \sqrt{|\mu_r||\epsilon_r|} \right) \quad (4)$$

The simulation of the matching thickness against the frequency according to this model is presented in Fig. 11a(ii) and b(ii). The multiplication sign ($\times$) in this figure represent the optimal thickness matching with the optimal frequency in the RL curves. The $\times$ signs that match with the simulation curve, which indicate that the absorption performance of the sample agrees with the quarter wavelength model. To evaluate the impedance matching degree, the $|Z_{in}/Z_0|$ values for the samples

evaluated and found to have a close value to unity (Fig. 11a(iii) and b(iii)) at the optimal thicknesses and matching frequencies indicating optimal impedance matching. The good impedance matching ensures that a huge fraction of the EM wave propagates across the material and results in enhanced absorption of EM wave. Besides, the good impedance matching which would ensure a small amount, or no EM wave reflect at the surface.

The ability of the sample to rapidly dissipate the trapped EM wave can be estimated by the attenuation constant (α) which largely depends on the magnitude of EM properties of the absorber. The α of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ samples is calculated using Eq. (5).

$$\alpha = \frac{\sqrt{2\pi f}}{c} \times \sqrt{(\mu''\epsilon'' - \mu'\epsilon') + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\mu'\epsilon'' + \mu''\epsilon')^2}} \quad (5)$$

where c is the EM velocity in free space, and f is the frequency. The evaluated attenuation abilities of the sample at 10 wt% and 20 wt% are presented in Fig. 12. The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters displayed poor EM wave attenuation ability at 10 wt% which explains the poor absorption achieved in the RL curve. While the good attenuation capacity at 20 wt% also justifies the good absorption achieved with this optimal loading. It can be concluded that both moderate attenuation and a good match of impedance are required for optimal EM wave absorption.

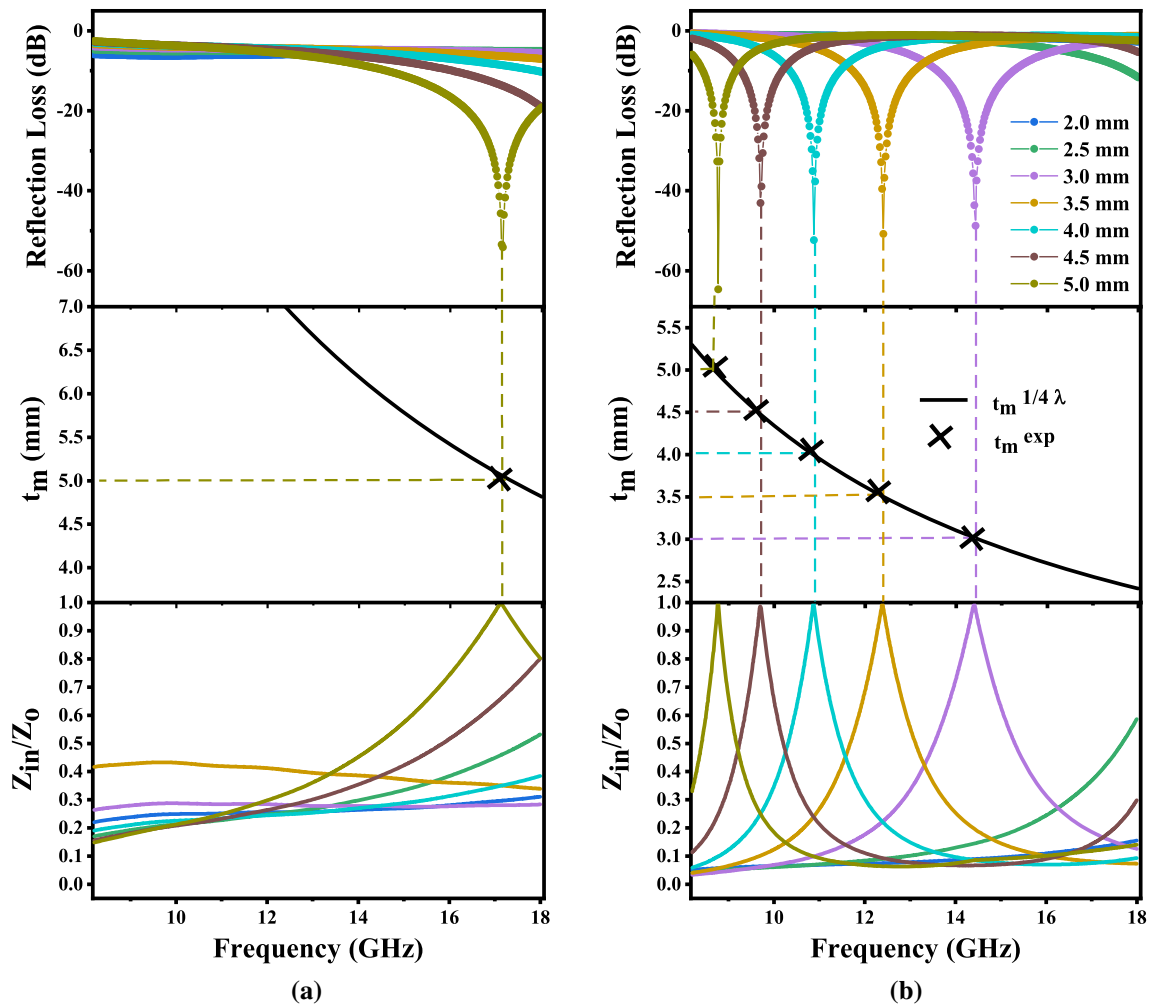


Fig. 11 (i) RL plot of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ (ii) simulated relationship between matching thicknesses (t_m) and matching frequency at quarter wavelength condition, and (iii) impedance matching conditions at different absorber thicknesses for (a) 10 wt%, and (b) 20 wt% loadings

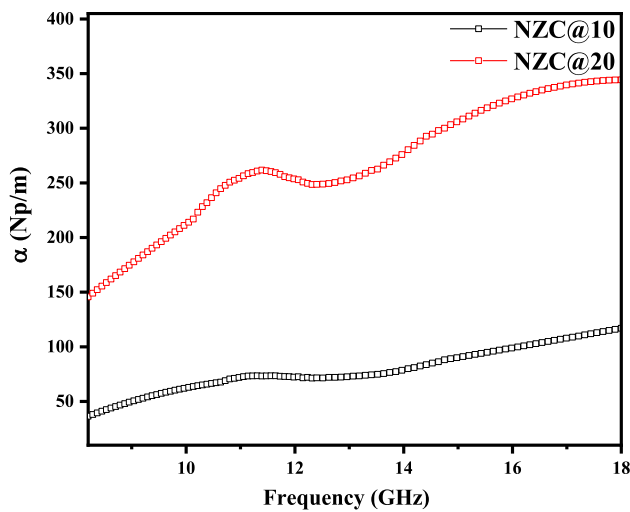


Fig. 12 Attenuation constant of the samples

4. Conclusion

$\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters with good morphology and structural properties were successfully prepared using simple co-precipitation and high-temperature calcination procedure. A paraffin composites with 20 wt% $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters display good EM wave absorption properties with a strong RL value and wide effective absorption bandwidth. An optimal RL of -48.8 dB was attained at 14.42 GHz, with 3.0 mm thickness. This EM wave absorption could be ascribed to the advantages of high EM properties as well as interfacial polarization mechanism. The sample also enjoy good impedance matching and high EM wave attenuation ability which collectively contributed to the satisfying EM wave absorption. In the end, the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoclusters prepared here can be regarded as ideal EM wave absorbing materials.

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