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R.N. Akhadi¹, B. Kurniawan¹, S.A. Saptari²

Tailoring the Electromagnetic Response of MoS₂ through Ni Doping for Promising Microwave Absorber

¹Department of Physics, University of Indonesia, Depok, Jawa Barat, Indonesia,

²Physics Department, Faculty of Science and Technology, Syarif Hidayatullah State Islamic University Jakarta, Tangerang Selatan, Banten, Indonesia, sitti.ahmiatri@uinjkt.ac.id

Transition-metal doping offers a promising route to enhance the microwave absorption performance of layered materials. In this work, Ni-doped MoS₂ nanostructures with varying concentrations (0–4 at%) were synthesized via a hydrothermal method to systematically investigate the effect of Ni incorporation on structural, magnetic, and electromagnetic properties. XRD analysis confirmed that Ni doping preserved the hexagonal MoS₂ phase while inducing lattice contraction and reduced crystallite size. SEM observations revealed increasingly compact agglomerated nanosheet-flower morphologies with higher Ni content, indicative of enhanced nucleation and crystal growth. VSM measurements demonstrated that Ni doping significantly improved magnetic properties, with the 4 at% sample exhibiting the highest saturation magnetization (1.101 emu/g) and lowest coercivity (830 Oe), characteristic of soft ferromagnetism. Microwave absorption tests in the X-band (8–12 GHz) showed that Ni doping markedly increased reflection loss and broadened the effective bandwidth. Optimal performance was achieved at 4% Ni, with a maximum reflection loss of –27.91 dB ($\approx$ approximately 99.84% absorbance) at 10.60 GHz and an effective bandwidth of 0.64 GHz. These findings highlight Ni doping as an effective strategy to tailor the electromagnetic response of MoS₂, offering strong potential for stealth technology and electromagnetic interference (EMI) shielding applications.

Keywords: Microwave absorption, Ni-doped MoS₂, hydrothermal synthesis, magnetic properties, reflection loss.

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Introduction

The continuous growth of modern communication technologies has led to increased human exposure to electromagnetic radiation, especially within the microwave spectrum [1]. This situation not only raises potential health concerns but also drives the demand for stealth materials in defense systems, where effective attenuation of radar signals is crucial [2], [3]. Consequently, microwave absorbing materials (MAMs) have attracted significant research interest due to their ability to reduce reflected and transmitted electromagnetic waves, thereby enhancing electromagnetic compatibility and stealth performance [4], [5], [6].

High-performance microwave absorbing materials (MAMs) are expected to combine strong dielectric and

magnetic losses with high reflection loss (RL), wide bandwidth, and low density [7], [8], [9]. Among various candidates, molybdenum disulfide (MoS₂) has attracted attention due to its layered structure, tunable bandgap, and promising dielectric loss capability [10], [11], [12]. However, pristine MoS₂ is intrinsically diamagnetic, which limits its microwave absorption efficiency [13], [14], [15]. To overcome this limitation, strategies that introduce magnetic functionality into MoS₂ are required [14].

Doping with transition metals has emerged as a reliable route to tune the electronic and magnetic properties of layered compounds [16], [17], [18]. In particular, nickel incorporation has been reported to induce ferromagnetism in MoS₂, thereby improving saturation magnetization and stabilizing magnetic

ordering at room temperature. Previous studies also noted that Ni doping enhances microwave absorption, though systematic evaluations linking doping concentration with structural evolution, magnetic enhancement, and absorption efficiency remain scarce [19]. Nevertheless, systematic investigations that correlate Ni doping levels with structural evolution, magnetic enhancement, and microwave absorption efficiency remain limited.

In this study, Ni-doped MoS₂ nanostructures with controlled doping levels (0–4 at%) were synthesized using a hydrothermal route to clarify the relationship between Ni incorporation, crystal structure, morphology, magnetic behavior, and microwave absorption. Comprehensive characterization through X-ray diffraction (XRD), scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), vibrating sample magnetometry (VSM), and vector network analysis (VNA) was conducted to determine the optimal Ni concentration that balances dielectric and magnetic losses. This work not only advances the understanding of transition metal-doped MoS₂ but also highlights its potential as a high-performance microwave absorber for stealth technology and next-generation communication devices.

I. Experimental

Synthesis of Samples

Ni-doped MoS₂ nanostructures with varying Ni concentrations (0, 2, 3, and 4 at%) were synthesized via a hydrothermal method [20]. Analytical-grade sodium molybdate dihydrate (Na₂MoO₄·2H₂O), thiourea (NH₂CSNH₂), and nickel (II) nitrate hexahydrate (Ni(NO₃)₂·6H₂O) were employed as precursors without further purification. The stoichiometric amounts of each precursor were calculated according to the targeted doping levels and precisely weighed using a digital microbalance, as summarized in Table 1.

Each precursor was dissolved in 30 mL of deionized water under continuous magnetic stirring for 1 h to ensure complete homogenization. The resulting solution was transferred into a Teflon-lined stainless-steel autoclave and subjected to hydrothermal treatment at 200°C for 24 h. After cooling to room temperature, the precipitates were collected, centrifuged, and washed sequentially with ethanol and deionized water (two cycles each) to remove residual ions and unreacted species. The washed powders were dried on a hot plate at 60°C for 12 h to obtain the final Ni-doped MoS₂ samples.

Characterization

The phase composition and crystallinity of the synthesized samples were examined using X-ray

diffraction (XRD, Panalytical Malvern) with Cu-Kα radiation ($\lambda = 1.5406 \text{ \AA}$). Morphological features and elemental composition were analyzed by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS, FEI Quanta 650 with Oxford EDS detector). Magnetic properties were measured at room temperature using a vibrating sample magnetometer (VSM, Oxford type 1.2H), recording magnetization (M–H) hysteresis loops.

Microwave absorption measurements were carried out using an Anritsu MS46322A vector network analyzer in the X-band frequency range (8–12 GHz). The Ni-doped MoS₂ powders obtained from hydrothermal synthesis were directly pressed into rectangular pellets with a thickness of 1.5 mm and measured in a WR-90 rectangular waveguide fixture. A metal-backed configuration was employed, and 1-port calibration was performed using the short-open-load method. Reflection loss (RL) was calculated from the measured scattering parameters using the input impedance model according to the following equation:

$$RL(dB) = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right|, \quad (1)$$

where Z_{in} is the input impedance of the absorber backed by a metal plate, and Z_0 is the impedance of free space. Measurements were conducted in a metal-backed configuration to ensure negligible transmission. Therefore, the reported percentages represent absorption efficiency calculated from reflection loss values. This detailed description ensures reproducibility of the results.

II. Result and Discussion

Crystal Structure and Phase

The XRD patterns of Ni-doped MoS₂ with varying concentrations (0, 2, 3, and 4 at%) are presented in Figure 1. All samples exhibited broad and low-intensity diffraction peaks, indicative of low crystallinity. The diffraction profiles matched well with the standard JCPDS card No. 37-1492, corresponding to molybdenite (2H-MoS₂) with a hexagonal phase. Importantly, the Ni-doped samples (2–4 at%) displayed diffraction peaks similar to those of pristine MoS₂, suggesting that Ni addition does not alter the overall crystal structure. This behavior is consistent with previous reports, where Ni doping below 10 at% does not introduce additional diffraction peaks, although the precise incorporation mechanism (substitutional vs. interstitial) cannot be conclusively determined [21], [22], [23].

Table 1.

Calculated precursor amounts for the synthesis of Ni-doped MoS₂ nanostructures at different Ni concentrations (0–4 at%).

Ni-doped	Na ₂ MoO ₄ ·2H ₂ O (gram)	NH ₂ CSNH ₂ (gram)	Ni(NO ₃) ₂ ·6H ₂ O (gram)
0 at%	0.7257	1.1421	0.0000
2 at%	0.7257	1.1421	0.0174
3 at%	0.7257	1.1421	0.0262
4 at%	0.7257	1.1421	0.0349

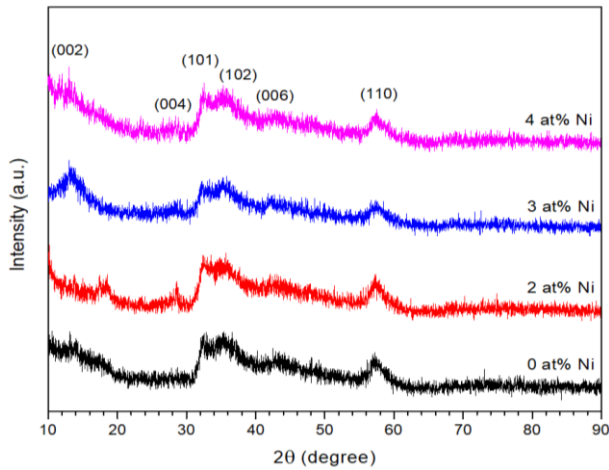


Fig.1. XRD patterns of Ni-doped MoS₂ samples (0–4 at%), showing diffraction peaks of the 2H phase with systematic shifts toward higher angles as Ni content increases.

To further validate the crystallinity and lattice distortion induced by Ni addition, the (110) diffraction peak of the synthesized samples was analyzed in detail. Parameters, including the full width at half maximum (FWHM), interplanar spacing (d_{110}), and crystallite size, were extracted to quantify structural changes. The refinement results are summarized in Table 2. A systematic shift of the (110) peak toward higher diffraction angles was observed with increasing Ni content, consistent with structural modification associated with Ni doping. Concurrently, the d -spacing decreased, and the FWHM broadened, indicating enhanced lattice strain and reduced crystallite size. These findings corroborate the XRD observations and suggest that Ni doping introduces subtle structural distortions without altering the overall hexagonal phase of MoS₂, thereby providing additional defect sites and polarization centers that are beneficial for microwave absorption.

As summarized in Table 2, the (110) diffraction peak progressively shifted toward higher angles with increasing Ni content, reflecting lattice contraction induced by Ni incorporation. This trend is consistent with earlier reports, where Ni doping was shown to cause systematic peak shifts due to substitutional diffusion [22]. The corresponding interplanar spacing (d_{110}) decreased as the doping level increased, which may be related to lattice distortion effects. Notably, the smaller atomic radius of Ni (1.49 Å) compared to Mo (1.90 Å) [24] provides a possible explanation for the observed contraction, although the precise substitution mechanism cannot be

conclusively established from XRD alone. In parallel, the full width at half maximum (FWHM) broadened with higher Ni concentrations, indicating enhanced lattice strain and reduced crystallite size. Peak broadening and size reduction suggest that Ni doping introduces lattice defects and strain, providing polarization centers that enhance microwave absorption.

Overall, the XRD analysis highlights that Ni doping induces peak shifts, lattice strain, and reduced crystallite size, suggesting the presence of structural distortions and defect sites within the MoS₂ lattice. These crystallographic modifications are expected to influence particle assembly and surface architecture. To verify this correlation, the morphology of the synthesized samples was subsequently examined using SEM, providing complementary insights into how Ni addition governs nucleation, agglomeration, and the formation of hierarchical nanosheet-flower structures.

Morphology and Elemental

The morphology of Ni-doped MoS₂ was examined using SEM, as shown in Figure 2 for samples with 0, 2, 3, and 4 at% Ni. At low magnification (Figures 2a–d), all samples exhibited agglomerated particles formed by the stacking of secondary structures. With increasing Ni content, the agglomerates became progressively smaller, denser, and more compact, accompanied by an increase in the number of agglomeration sites. This trend suggests that Ni incorporation promotes nucleation and accelerates crystal growth within the MoS₂ matrix [25], [26]. At higher magnification (Figures 2e–h), the secondary structures of all samples revealed a characteristic nanosheet-flower morphology, in which ultrathin nanosheets are radially assembled into spherical aggregates [21], [27]. Such hierarchical architectures are known to enhance microwave absorption by increasing multiple scattering pathways and providing abundant defect sites for dipolar polarization [28].

The SEM analysis revealed that Ni doping promotes the formation of hierarchical nanosheet-flower structures and increases particle agglomeration. To confirm that these morphological changes are directly associated with Ni incorporation, elemental composition was examined using energy-dispersive X-ray spectroscopy (EDS). As shown in Figure 3, the pristine MoS₂ sample contains only Mo and S elements, consistent with its stoichiometric composition, whereas the Ni-doped samples (2–4 at%) exhibit additional Ni signals alongside Mo and S. Together with the absence of detectable secondary XRD peaks, these results suggest that Ni is incorporated into the MoS₂ framework.

Table 2.

Structural refinement parameters of Ni-doped MoS₂ samples (0–4 at%), showing peak shifts, reduced interplanar spacing, broadened FWHM, and smaller crystallite sizes while retaining the hexagonal 2H-MoS₂ phase.

Parameters	Ni-doped			
	0 at%	2 at%	3 at%	4 at%
Structure	Hexagonal	Hexagonal	Hexagonal	Hexagonal
Space group	P63/mmc	P63/mmc	P63/mmc	P63/mmc
$2\theta_{(110)}$	57.201	57.265	57.432	57.502
$d_{(110)}$ (Å)	1.609	1.608	1.603	1.601
FWHM ₍₁₁₀₎	1.913	1.977	1.980	1.997
Crystallite size ₍₁₁₀₎ (Å)	47.311	45.762	45.754	45.365

However, the precise lattice position of Ni (substitutional vs. interstitial) cannot be conclusively determined from XRD and EDS alone. Alternative possibilities, including surface-associated Ni species or undetected secondary phases, may also contribute. Quantitative results of elemental distribution, expressed in both weight and atomic percentages, are summarized in Table 3, reflecting controlled doping levels and compositional accuracy.

As presented in Table 3, the atomic ratio of Mo to S in the pristine MoS₂ sample was 1:1.84, which closely approaches the ideal stoichiometric ratio of 1:2, thereby confirming the successful formation of MoS₂ in the synthesized product. In the Ni-doped samples, the atomic percentage of Ni increased proportionally with the precursor concentration, reflecting precise control over the doping process. Notably, the 3 at% Ni-doped sample exhibited a Ni atomic composition consistent with the intended precursor ratios, validating both the accuracy of the synthesis procedure and the reproducibility of the

doping strategy. While these results confirm the presence and controlled addition of Ni, the exact lattice incorporation (substitutional vs. interstitial) cannot be conclusively determined from EDS alone [21].

The EDS analysis confirmed the presence of Ni in the MoS₂ samples with controlled doping concentrations and high sample purity. Together with the absence of detectable secondary XRD peaks, these results suggest Ni incorporation into the MoS₂ framework, although the precise lattice position (substitutional vs. interstitial) cannot be conclusively determined from EDS alone. Having established the structural and compositional accuracy of the synthesized products, it is essential to investigate how Ni doping influences their magnetic behavior. Therefore, the magnetic properties of Ni-doped MoS₂ were examined using vibrating sample magnetometry (VSM), providing insights into the role of Ni doping in modulating magnetization and defect-induced magnetic responses.

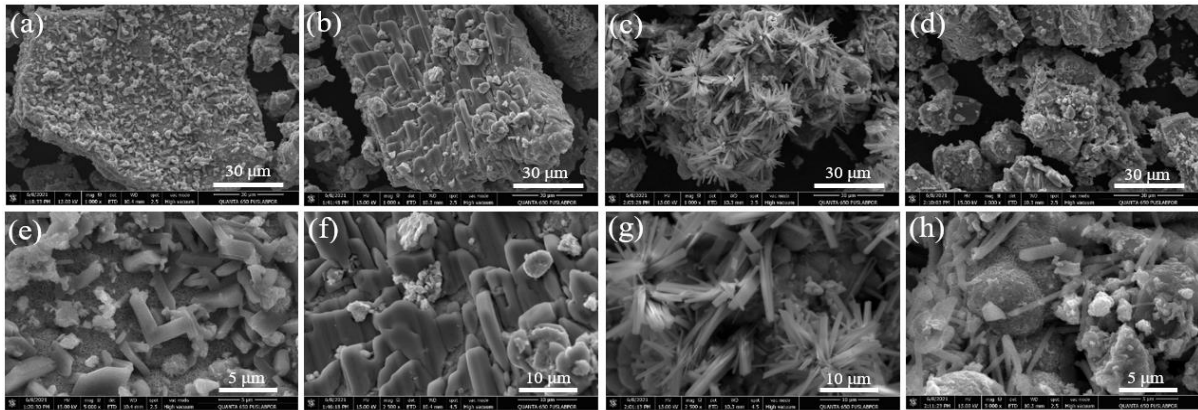


Fig. 2. SEM images of Ni-doped MoS₂ samples (0–4 at%). Low-magnification views (a–d) show progressively smaller and more compact particles with increasing Ni content, while high-magnification views (e–h) reveal hierarchical flower-like nanosheet assemblies.

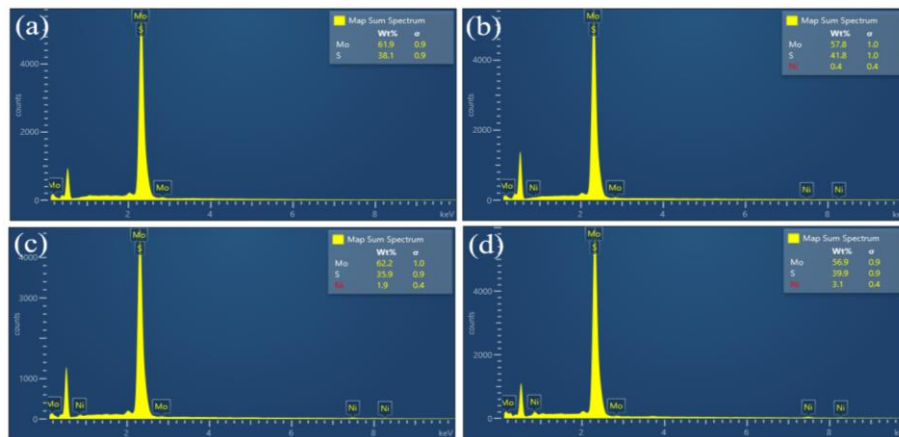


Fig. 3. EDS spectra of Ni-doped MoS₂ samples (0–4 at%).

Table 3.

Quantitative EDS analysis of Ni-doped MoS₂ samples (0–4 at%).

Element	Ni-doped							
	0 at%		2 at%		3 at%		4 at%	
	wt%	at%	wt%	at%	wt%	at%	wt%	at%
Mo	61.92	35.21	57.79	31.48	62.2	36.02	56.93	31.35
S	38.08	64.79	41.81	68.15	35.87	62.15	39.95	65.83
Ni	0	0	0.41	0.37	1.93	1.83	3.13	2.82

Magnetic Properties

To evaluate the magnetic behavior of Ni-doped MoS₂, vibrating sample magnetometry (VSM) was employed to record the hysteresis loops of the samples at room temperature. The hysteresis curves of MoS₂ with varying Ni concentrations (0, 2, 3, and 4 at%) are presented in Figure 4, providing direct evidence of the influence of Ni incorporation on the magnetic response of the material.

As shown in Figure 4, all samples exhibit clear hysteresis loops, confirming their ferromagnetic behavior at room temperature. This observation is consistent with the findings of Martinez et al. (2018), who reported that hydrothermally synthesized MoS₂ displays weak ferromagnetism, while Ni-doped MoS₂ demonstrates enhanced ferromagnetic characteristics [29]. The origin of this ferromagnetism is primarily attributed to structural defects generated during hydrothermal synthesis, such as zigzag edges and sulfur vacancies, which act as localized magnetic centers [30]. The corresponding magnetic parameters, including saturation magnetization, remanence, and coercivity, are summarized in Table 4, providing quantitative evidence of the influence of Ni incorporation on the magnetic response of MoS₂.

For magnetic absorbing materials (MAMs), critical parameters include high saturation magnetization (M_s), substantial remanence (M_r), and low coercivity (H_c). As summarized in Table 4, M_s progressively increases with Ni incorporation, peaking at 4 at%. Meanwhile, M_r rises to 3 at% before dropping sharply at higher doping, and H_c varies with concentration, reaching its minimum at 4 at%. Collectively, these findings indicate that the 4 at% Ni-doped MoS₂ sample exhibits a magnetic profile that may be favorable for absorber applications, though static VSM parameters alone do not directly quantify microwave losses. The enhancement in M_s near 3 at% Ni is consistent

with prior reports, which linked this behavior to orbital coupling between Ni 3d and S 2p states [31], [32]. Unlike earlier reports that observed a decline in M_s beyond 3 at%, our results reveal a steady increase up to 4 at%, confirming the effectiveness of Ni addition in tuning the magnetic response [21].

Table 4.

Magnetic parameters of Ni-doped MoS₂ samples (0–4 at%). Saturation magnetization (M_s), remanence (M_r), and coercivity (H_c) increase with Ni content, reflecting the influence of Ni incorporation and defect-related magnetic centers on the overall response.

Ni-doped	M_s (emu/gram)	M_r (emu/gram)	H_c (Oe)
0 at%	1.054	0.104	1080
2 at%	1.056	0.115	925
3 at%	1.100	0.120	1150
4 at%	1.101	0.022	830

Having established the magnetic properties of Ni-doped MoS₂, it is crucial to evaluate their electromagnetic performance, particularly in terms of microwave absorption. Vibrating sample magnetometry (VSM) results provide useful context for correlating magnetic parameters with absorption behavior, but direct verification requires vector network analyzer (VNA) measurements of frequency-dependent electromagnetic parameters. Therefore, the reflection loss and electromagnetic response of the samples were investigated using a VNA to assess their potential as promising microwave absorbing materials.

Microwave Absorption Properties

Reflection loss (RL) analysis was conducted to evaluate the microwave absorption capability of Ni-doped

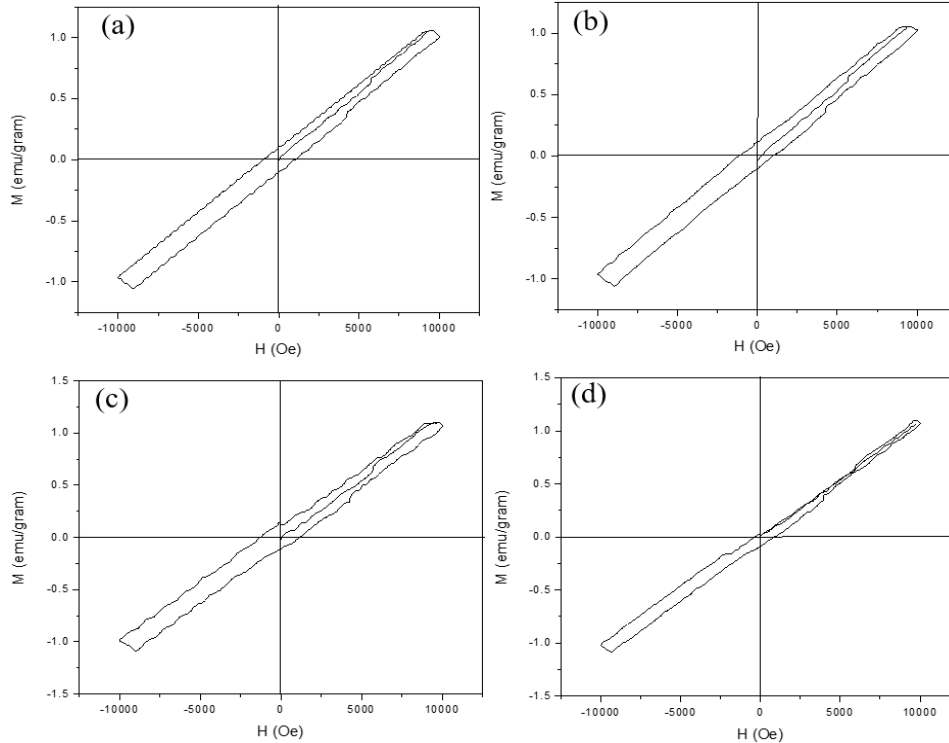


Fig. 4. Room-temperature hysteresis loops of Ni-doped MoS₂ samples with varying Ni concentrations (0–4 at%). Progressive changes in magnetization with increasing Ni content highlight the influence of Ni incorporation on the magnetic response.

MoS₂. Figure 5 and Table 5 present the RL values of MoS₂ powders with different Ni concentrations (0, 2, 3, and 4 at%) measured at a thickness of 1.5 mm within the frequency range of 8–12 GHz. These results provide direct insight into the influence of Ni incorporation on the electromagnetic response of MoS₂, highlighting the role of doping concentration in modulating absorption performance.

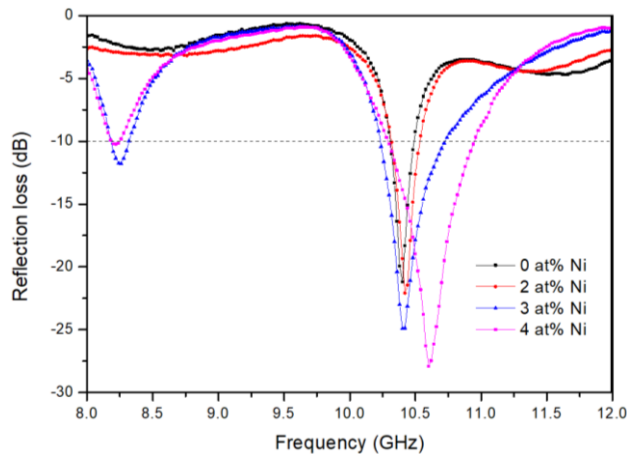


Fig. 1. Reflection loss (RL) curves of Ni-doped MoS₂ samples (0–4 at%) measured at 1.5 mm thickness in the 8–12 GHz range. The variation in RL with Ni concentration illustrates the role of Ni incorporation in enhancing microwave absorption.

Figure 5 illustrates that Ni incorporation exerts a pronounced effect on the microwave absorption behavior of MoS₂. Relative to the pristine sample, Ni-doped specimens display superior attenuation, reflected in higher maximum reflection loss (RL) values and broader effective bandwidths. With increasing Ni concentration, RL progressively improves, and more frequency points exceed the –10 dB criterion. The best performance is observed at 4 at% Ni, achieving a maximum RL of –27.91 dB ($\approx 99.84\%$ absorption efficiency) at 10.60 GHz, together with an effective bandwidth of 0.64 GHz spanning 10.30–10.94 GHz.

The microwave absorption behavior is closely correlated with the magnetic properties of the samples. The most favorable magnetic parameters for magnetic absorbing materials (MAMs) were obtained at 4 at% Ni doping, which exhibited the highest saturation magnetization ($M_s = 1.101$ emu/g) and the lowest coercivity ($H_c = 830$ Oe). These magnetic characteristics directly contribute to the enhanced microwave absorption,

as reflected by the highest RL value and the broadest effective bandwidth observed at this doping level. This correlation confirms that the improvement in magnetic properties plays a decisive role in modulating the microwave absorption performance of Ni-doped MoS₂.

Taken together, the structural, morphological, compositional, and magnetic analyses consistently demonstrate that Ni doping effectively tailors the properties of MoS₂ for microwave absorption applications. XRD results confirmed lattice distortions and reduced crystallite size upon Ni incorporation, while SEM revealed hierarchical nanosheet-flower morphologies that promote multiple scattering of incident microwaves. EDS verified the successful incorporation of Ni without impurities, ensuring compositional accuracy. VSM analysis established the enhancement of magnetic parameters, particularly at 4 at% doping, which directly translated into superior microwave absorption performance as validated by VNA measurements.

Overall, this study highlights the synergistic effect of Ni doping on both magnetic and electromagnetic properties of MoS₂. The optimized sample at 4 at% Ni doping exhibited the best balance of high saturation magnetization, low coercivity, and strong microwave attenuation, achieving nearly complete absorption efficiency at specific frequencies. These findings not only confirm the potential of Ni-doped MoS₂ as a promising candidate for magnetic absorbing materials but also provide a comprehensive understanding of the structure–property–performance relationship, offering valuable guidance for the design of next-generation microwave absorbers.

To benchmark the microwave absorption performance obtained in this study, recent reports on MoS₂-based absorbers are summarized in Table 6. Several studies have demonstrated that interface engineering and compositional modification can significantly enhance absorption properties, achieving RL values below –50 dB with wide effective bandwidths. In comparison, the Ni-doped MoS₂ synthesized here achieved a maximum RL of –27.91 dB at 10.60 GHz with an effective bandwidth of 0.64 GHz, confirming competitive performance while maintaining a simple and reproducible hydrothermal synthesis route.

This comparison highlights both the effectiveness of Ni doping and the opportunities for further improvement through multi-interface design strategies.

Compared to recent MoS₂-based composites that achieved RL values below –50 dB, the Ni-doped MoS₂

Table 5.

Reflection loss (RL) data of Ni-doped MoS₂ samples (0–4 at%) measured at 1.5 mm thickness in the 8–12 GHz range. The values reveal the effect of Ni incorporation on microwave absorption, with enhanced attenuation observed at higher doping levels.

Ni-doped	RLmax (dB)	Freq. (GHz)	Bandwidth (GHz)	Freq. range (GHz)	Absorption efficiency (%)
0 at%	-21.17	10.40	0.16	10.32 – 10.48	99.24
2 at%	-22.08	10.42	0.2	10.32 – 10.52	99.38
3 at%	-11.78	8.26	0.1	8.20 – 8.30	93.36
	-24.91	10.40	0.48	10.24 – 10.72	99.68
4 at%	-10.23	8.22	0.04	8.20 – 8.24	90.52
	-27.91	10.60	0.64	10.30 – 10.94	99.84

Table 6.

Comparison of microwave absorption performance (RL values and bandwidth) of MoS₂-based absorbers reported in recent literature and the present work.

Materials	thickness (mm)	RLmax (dB)	Freq. (GHz)	Bandwidth (GHz)	Freq. range (GHz)	Absorption efficiency (%)	Ref.
Ni-doped MoS ₂	1.5	-27.91	10.60	0.64	10.30 – 10.94	99.84	This work
MoS ₂ /BN	4	-32.21	-	8.68	9.32 - 18.00	-	[33]
MoS ₂ /polyethersulfone	0.45	-95.32	21.28	7.61	-	-	[34]
MoS ₂ /carbon	1.5	-41.60	8.96	4.32	-	-	[35]
Fe-doped MoS ₂	1.61	-60.60	-	5.1	-	-	[36]
V-doped MoS ₂	1.78	-32.24	-	4.40	-	99.9	[37]
Morphology-tuned MoS ₂ nanostructures		-21.77	9.6	-	-	-	[38]

synthesized in this work demonstrates competitive absorption performance while maintaining a simple hydrothermal route, confirming its promise as a reproducible microwave absorber.

Conclusions

In this study, Ni-doped MoS₂ was successfully synthesized and comprehensively characterized to assess its potential as a microwave-absorbing material. Structural analysis confirmed lattice distortions and a reduction in crystallite size upon Ni incorporation, while SEM revealed hierarchical nanosheet-flower morphologies that promote multiple scattering of incident microwaves. EDS verified the successful incorporation of Ni without impurities, ensuring compositional accuracy. VSM analysis demonstrated enhanced magnetic properties, particularly at 4% Ni doping, which exhibited the highest saturation magnetization and the lowest coercivity. VNA measurements further validated the superior microwave absorption performance of the 4 at% Ni-doped sample, achieving a maximum reflection loss of -27.91 dB (99.84% absorption efficiency) at 10.60 GHz with an

effective bandwidth of 0.64 GHz.

Overall, the results highlight the synergistic role of Ni doping in tailoring both magnetic and electromagnetic properties of MoS₂. The optimized 4 at% Ni-doped MoS₂ sample exhibited the best balance of structural integrity, magnetic enhancement, and microwave attenuation, confirming its promise as a magnetic absorbing material. These findings provide valuable insights into the structure–property–performance relationship of doped transition metal dichalcogenides, offering a solid foundation for the rational design of next-generation microwave absorbers.

R.N. Akhadi – Undergraduate student, Department of Physics, University of Indonesia;

B. Kurniawan – Dr., Associate Professor, Department of Physics, University of Indonesia;

S.A. Saptari – Dr., Associate Professor, Physics Department, Faculty of Science and Technology, UIN Syarif Hidayatullah Jakarta.

- [1] J. C. Lin, *Health and safety practices and policies concerning human exposure to RF/microwave radiation*, Frontiers Media SA. (2025); <https://doi.org/10.3389/fpubh.2025.1619781>.
- [2] S.H. Siddiki, C.K. Maity, and S. Sahoo, *Advances in microwave-absorbing materials: from fundamentals to emerging technologies*, J. Mater. Chem. A, 13(38), 31869 (2025); <https://doi.org/10.1039/D5TA03936C>.
- [3] J. Ren et al., *Multifunctions of microwave-absorbing materials and their potential cross-disciplinary applications: a mini-review*, Adv. Compos. Hybrid Mater., 8(2), 202 (2025); <https://doi.org/10.1007/s42114-025-01258-5>.
- [4] F. Giannazzo, S. E. Panasci, E. Schilirò, A. Koos, and B. Pécz, *Integration of graphene and MoS₂ on silicon carbide: Materials science challenges and novel devices*, Mater. Sci. Semicond. Process., 174, (2024); <https://doi.org/10.1016/j.mssp.2024.108220>.
- [5] X. Yang et al., *Co-Ni Electromagnetic Coupling in Hollow Mo₂C/NC Sphere for Enhancing Electromagnetic Wave Absorbing Performance*, Chin. J. Chem., 41(1), 64 (2023); <https://doi.org/10.1002/cjoc.202200475>.
- [6] H. Pang et al., *Research advances in composition, structure and mechanisms of microwave absorbing materials*, Compos. B Eng., 224, 109173 (2021); <https://doi.org/10.1016/j.compositesb.2021.109173>.
- [7] N. N. Ghosh, *Editorial: Dielectric microwave absorbing structures*, Frontiers Media S.A. (2023); <https://doi.org/10.3389/fmats.2023.1181978>.
- [8] U. Jamwal, S.K. Mittal, and D. Keneria, *Polarization and Ferromagnetism in Microwave-Absorbing Materials*, in Ferroic Materials - Understanding, Development, and Utilization, A. Hussain and M. Khan, Eds., London: IntechOpen, ch. 4, (2025); <https://doi.org/10.5772/intechopen.1006874>.

- [9] S.A. Saptari, J.Q. Syarifuddin, A. Tjahjono, H. Hadiyawarman, and G.E. Timuda, *Enhancement of microwave absorption ability of Nd_{0.67}Sr_{0.33}Mn_{1-x}Ni_x/2Ti_x/2O₃ (x = 0, 0.03, and 0.06)*, Emergent Mater., (2024); <https://doi.org/10.1007/s42247-024-00791-1>.
- [10] Z.D. Gerbi, *Electronic and optical properties of molybdenum disulfide (MoS₂) mono layer using density functional theory (DFT) calculations*, AIP Adv., 15(2), (2025); <https://doi.org/10.1063/5.0256769>.
- [11] P.-P. Zhou et al., *Multi-interface engineering of FeS₂/C/MoS₂ with core-shell structure for superior microwave absorption performance*, Rare Metals, 44 (6), 4095 (2025); <https://doi.org/10.1007/s12598-025-03264-4>.
- [12] H. Wang et al., *Progress in the use of MoS₂-based composites for microwave absorption*, Materials Science and Engineering: R: Reports, 161, 100838 (2024); <https://doi.org/10.1016/j.mser.2024.100838>.
- [13] Y. Ding et al., *Broadband electromagnetic wave absorption properties and mechanism of MoS₂/rGO nanocomposites*, Mater. Chem. Front., 5(13), 5063 (2021); <https://doi.org/10.1039/D1QM00364J>.
- [14] Y. Sani et al., *Recent Developments in Synthesis Techniques and Microwave Absorption Performance of Materials Based on Molybdenum Disulfide (MoS₂) with Metal Oxides: A Review*, Recent Prog. Mater., 07(01), 1 (2025); <https://doi.org/10.21926/rpm.2501003>.
- [15] M. Chen, C. Hu, X. Luo, A. Hong, T. Yu, and C. Yuan, *Ferromagnetic behaviors in monolayer MoS₂ introduced by nitrogen-doping*, Appl. Phys. Lett., 116 (7), 073102 (2020); <https://doi.org/10.1063/5.0001572>.
- [16] S.A. Toularoud, H. Hadipour, and H.R. Soleimani, *Engineering the electronic and magnetic properties of monolayer TiS₂ through systematic transition-metal doping*, Mar. 2024, [Online]. Available: <http://arxiv.org/abs/2403.15850>.
- [17] W. Chen et al., *Electronic and magnetic properties of transition-metal-doped monolayer B₂S₂ within GGA + U framework*, RSC Adv., 14 (5), 3390 (2024); <https://doi.org/10.1039/D3RA08472H>.
- [18] C. Fang, Z. Yan, X.-J. Zhang, J.-H. Xiao, F. Wang, and X.-H. Xu, *Stable geometries and magnetic properties in transition-metal-doped Sm₅Co₁₉ permanent magnet alloys: Insights from DFT*, Sci. China Phys. Mech. Astron., 68(4), 247512 (2025); <https://doi.org/10.1007/s11433-024-2593-5>.
- [19] Y. Liu, C. Ji, X. Su, X. He, J. Xu, and Y. Li, *Enhanced Microwave Absorption Properties of Flaky MoS₂ Powders by Decorating with Ni Particles*, J. Magn. Mater., 511, 166961 (2020); <https://doi.org/10.1016/j.jmmm.2020.166961>.
- [20] J. Li et al., *MoS₂-Based Nanocomposites for Microwave Absorption: A Review*, ACS Appl. Nano Mater., 7(6), 5761 (2024); <https://doi.org/10.1021/acsanm.4c00055>.
- [21] M. Farooq, T. Iqbal, K. N. Riaz, A. M. Ali, and A. F. A. El-Rehim, *Simple synthesis of Ni-doped MoS₂ nanoparticles and their application as efficient photocatalyst: experiment and COMSOL simulation*, Chemical Papers, 76(12), 7493 (2022); <https://doi.org/10.1007/s11696-022-02422-7>.
- [22] D. Mosconi et al., *Effect of Ni Doping on the MoS₂ Structure and Its Hydrogen Evolution Activity in Acid and Alkaline Electrolytes*, Surfaces, 2(4), 531 (2019); <https://doi.org/10.3390/surfaces2040039>.
- [23] M. Zhang et al., *Facile synthesis of 2D MoS₂/reduced graphene oxide hybrids with excellent microwave absorption*, J. Alloys Compd., 953, 170005 (2023); <https://doi.org/10.1016/j.jallcom.2023.170005>.
- [24] A. Manceau et al., *Natural speciation of Mn, Ni and Zn at the micrometer scale in a clayey paddy soil using X-ray fluorescence, absorption, and diffraction*, Geochim. Cosmochim. Acta, 4007 (2005); <https://doi.org/10.1016/j.gca.2005.03.018i>.
- [25] S. Cui et al., *Ni-Doped MoS₂/N-Doped Carbon Hollow Nanostructures for Sodium-Ion Half and Full Batteries*, ACS Omega, 10 (40), 46612 (2025); <https://doi.org/10.1021/acsomega.5c03587>.
- [26] V. M. Reddy, M. B. Chandra, S. Gengan, and S. Duraisamy, *Electrochemical nucleation and growth model of MoS₂ for hydrogen evolution reaction*, J. Anal. Sci. Technol., 15 (1), 53 (2024); <https://doi.org/10.1186/s40543-024-00466-w>.
- [27] S.J. Panchu, K. Raju, P. Singh, D. D. Johnson, and H. C. Swart, *High-Mass Loading of Flower-Like Ni-MoS₂ Microspheres Toward Efficient Intercalation Pseudocapacitive Electrode*, ACS Appl. Energy Mater., 1 (2022).
- [28] Y. Han, D. Lan, M. Han, Z. Xia, J. Zou, and Z. Jia, *Construction of flower-like MoS₂ decorated on Cu doped CoZn-ZIF derived N-doped carbon as superior microwave absorber*, Nano Res., 17(9), 8250 (2024); <https://doi.org/10.1007/s12274-024-6859-z>.
- [29] L. M. Martinez et al., *Magnetic and electrocatalytic properties of transition metal doped MoS₂ nanocrystals*, J. Appl. Phys., 124 (15), 153903 (2018); <https://doi.org/10.1063/1.5043208>.
- [30] L. Loh, Z. Zhang, M. Bosman, and G. Eda, *Substitutional doping in 2D transition metal dichalcogenides*, Nano Res., 14 (6), 1668 (2021); <https://doi.org/10.1007/s12274-020-3013-4>.
- [31] M. Shakil et al., *Structural and Magnetic Behavior of MoS₂ on Doping of Transition Metals: a DFT Study*, J. Supercond. Nov. Magn., 34 (12), 3441 (2021); <https://doi.org/10.1007/s10948-021-06074-8>.
- [32] C. Jia, B. Zhou, Q. Song, X. Zhang, and Z. Jiang, *Modulating the magnetic properties of MoS₂ monolayers by group VIII doping and vacancy engineering*, RSC Adv., 8(34), 18837 (2018); <https://doi.org/10.1039/C8RA01644E>.
- [33] H. Wen and W. Zhang, *Preparation of hierarchical MoS₂ microsphere/BN composites for microwave absorption and thermal management*, International Journal of Minerals, Metallurgy and Materials, 32(3), 718 (2025); <https://doi.org/10.1007/s12613-024-3001-x>.

- [34] H. Rezaei, F. Soltani-Mohammadi, H. Dogari, H. Ghafari, and R. Peymanfar, *Plasma-assisted doping of pyrolyzed corn husk strengthened by MoS₂/polyethersulfone for fascinating microwave absorbing/shielding and energy saving properties*, *Nanoscale*, 16 (40), 18962 (2024); <https://doi.org/10.1039/D4NR02576H>.
- [35] Y. Zhang et al., *Bagasse-based porous flower-like MoS₂/carbon composites for efficient microwave absorption*, *Carbon Letters*, 35(1), 145 (2025); <https://doi.org/10.1007/s42823-024-00832-z>.
- [36] Y. Yan et al., *Enhancing microwave absorption performance of MoS₂ by synergistic effect of Fe doping*, *Journal of Advanced Ceramics*, 14 (3), (2025); <https://doi.org/10.26599/JAC.2025.9221039>.
- [37] J. Zou and Q. Xie, *Study on the Absorbing Properties of V-Doped MoS₂*, *Ceramics*, 8(3), (2025); <https://doi.org/10.3390/ceramics8030084>.
- [38] R. Thayil and S. R. Parne, *Morphology-Tuned Molybdenum Dichalcogenide Nanostructures for Enhanced Microwave Absorption Studies*, *J. Electron. Mater.*, 54(10), 9315 (2025); <https://doi.org/10.1007/s11664-025-12190-1>.

Р.Н. Ахаді¹, Б. Курніаван¹, С.А. Саптарі²

Керування електромагнітним відгуком MoS₂ шляхом легування Ni для перспективних поглиначів мікрохвильового випромінювання

¹ Кафедра фізики, Університет Індонезії, Депок, Західна Ява, Індонезія;

² Кафедра фізики, Факультет науки і технологій, Державний ісламський університет імені Шаріфа Хідаятулли в Джакарті, Південний Тангеранг, Бантен, Індонезія, sitti.ahmianti@uinjkt.ac.id

Легування перехідними металами є перспективним підходом до покращення здатності шаруватих матеріалів поглинати мікрохвильове випромінювання. У цій роботі наноструктури MoS₂, леговані Ni з різною концентрацією (0–4 ат.%), було синтезовано гідротермальним методом для систематичного дослідження впливу введення Ni на структурні, магнітні та електромагнітні властивості. X-променевий структурний аналіз (XRD) підтвердив, що легування Ni зберігає гексагональну фазу MoS₂, водночас спричиняючи стискання кристалічної ґратки та зменшення розміру кристалітів. СЕМ-дослідження показали, що зі збільшенням вмісту Ni формуються дедалі щільніші агломеровані структури типу «нанолисток - квітка», що свідчить про інтенсифікацію процесів зародкоутворення та росту кристалів. Вимірювання методом вібраційної магнітометрії (VSM) продемонстрували, що легування Ni суттєво покращує магнітні властивості. Зразок із вмістом Ni 4 ат.% характеризувався найбільшою намагніченістю насичення (1,101 емо/г) та найменшою коерцитивною силою (830 Е), що є характерним для магнітом'якої феромагнітної поведінки. Дослідження поглинання мікрохвильового випромінювання в Х-діапазоні (8–12 ГГц) показали, що легування Ni суттєво збільшує втрати на відбиття та розширює ефективну смугу поглинання. Оптимальні характеристики отримано за вмісту 4 ат.% Ni: максимальні втрати на відбиття становили –27,91 дБ (що відповідає поглинанню приблизно 99,84 %) на частоті 10,60 ГГц, а ефективна ширина смуги – 0,64 ГГц. Отримані результати свідчать про те, що легування Ni є ефективним способом керування електромагнітним відгуком MoS₂ та демонструють значний потенціал цього матеріалу для застосування в технологіях радіолокаційної малопомітності (stealth) і для екранування електромагнітних завад (EMI).

Ключові слова: поглинання мікрохвильового випромінювання; MoS₂, легований Ni; гідротермальний синтез; магнітні властивості; втрати на відбиття.