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Development of Printable Graphene/Ag Nanowire Conductive Ink for Electromagnetic Wave Absorption

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ABSTRACT

This study reports the formulation and implementation of a graphene/Ag nanowire (AgNW) hybrid conductive ink tailored for printed metamaterial-based electromagnetic (EM) wave absorbers. Graphene nanoplatelets (5 - 20 µm lateral size) provide abundant interfaces and dielectric loss, while high–aspect-ratio Ag nanowires (50 - 100 nm diameter, micrometer-scale length) establish efficient conductive pathways at low filler content. The ink shows good dispersion stability and printability, enabling accurate pattern transfer onto paper substrates. A cross-shaped metasurface geometry (l_1 = 18 mm, l_2 = 15 mm, w_1 = 8 mm) is employed to investigate absorber behavior. Microstructural characterization confirms the formation of an interconnected 2D–1D network, favorable for charge transport and electromagnetic loss. Measured and simulated results indicate effective EM energy dissipation and stable absorption under oblique incidence conditions up to 60°. The proposed ink system and printing approach offer a practical route for lightweight, flexible, and scalable EM absorber fabrication.

Introduction

Electromagnetic (EM) wave absorption materials are becoming a practical requirement in modern electronics, not only for electromagnetic interference (EMI) mitigation but also for radar signature management, wireless coexistence, and the reliability of compact, high-frequency systems [1, 2]. In the microwave regime, effective absorbers must simultaneously attenuate incident energy and minimize reflection at the air-material interface [3]. Reviews on graphene-based microwave absorbing materials consistently point out that balancing attenuation loss and impedance matching is the central challenge, and that structural design (porosity, hierarchical interfaces, hybrid fillers) often matters as much as intrinsic material properties [4, 5].

Among lightweight carbon-based candidates, graphene and its derivatives attract sustained interest because they can provide high dielectric loss with low density, rich interfacial polarization sites, and a tunable conductive network when dispersed into polymers or

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foams [6]. However, "graphene alone" rarely solves the full absorption problem. A highly conductive graphene network can increase conduction loss but may also worsen impedance matching by reflecting EM waves at the surface; conversely, a weakly conductive dispersion may match impedance better but lacks sufficient attenuation. This trade-off explains why graphene-based absorbers frequently adopt hybrid strategies, where graphene is combined with other conductive or lossy phases to engineer both the complex permittivity and the microstructure for multiple reflections and scattering pathways [7].

Compared with conventional copper foils or rigid laminates, conductive inks enable scalable fabrication routes such as screen printing, gravure, and inkjet printing, which are attractive for flexible devices and conformal EM coatings [8]. For metamaterial absorbers in particular, the top patterned conductive layer is the key element that shapes resonant and broadband absorption; typical designs consist of a periodic conductive metasurface, a dielectric spacer, and a reflective backplane.

Silver nanowires (AgNWs) are a compelling conductive filler for such inks [9]. Due to their high aspect ratio, AgNWs can form percolated networks at relatively low loadings, potentially reducing ink viscosity penalties and preserving flexibility. Reviews on AgNW inks emphasize that printed AgNW films can achieve high conductivity and mechanical compliance, and that conductivity, adhesion, and stability can be improved through formulation and post-processing choices compatible with low-temperature substrates [10]. A hybrid graphene/AgNW ink therefore offers a rational route to reconcile competing requirements in EM absorbers: graphene contributes lightweight dielectric loss and abundant interfaces, while AgNWs provide robust electrical pathways that strengthen conduction loss and enable stable, printable patterns [11, 12]. Hybrid conductive inks are already recognized as a practical strategy to tailor graphene ink performance for flexible and wearable electronics, supporting the broader premise that combining carbon nanomaterials with metallic nanostructures can move printed conductors closer to device-grade performance.

Motivated by these needs, this study focuses on the fabrication and application of a conductive graphene/AgNW ink designed for EM wave absorption structures. The work targets a formulation that remains printable, achieves a continuous conductive network after deposition, and integrates well with flexible substrates used in absorber stacks. Beyond achieving low sheet resistance, the ink must support absorber-relevant pattern fidelity and durability, since slight deviations in metasurface geometry can shift resonance and degrade absorption bandwidth.

Experimental

Chemical

Ethylene glycol, polyvinylpyrrolidone (PVP), $AgNO_3$, acetone, and ethyl acetate (EA) were supplied by Sigma-Aldrich. Modified graphene nanoplatelets were obtained from VNgraphene, while solvents, polymers, and silver precursors were supplied by Sigma-Aldrich. Photo paper substrates were provided by Kodak Vietnam. All chemicals were used as received.

Methods

Synthesis of Ag nanowires

Silver nanowires were synthesized via a polyol method using $CuCl_2$ as a structure-directing agent. A 0.03 M $CuCl_2$ solution was first prepared. Ethylene glycol and PVP were heated and stirred until fully dissolved, then cooled. $AgNO_3$ was added and mixed, followed by rapid injection of the $CuCl_2$ solution. The mixture was heated at 130 °C for 4 h to form nanowires, which were purified by acetone precipitation and redispersed in ethanol.

Fabrication of graphene/Ag nanowire conductive ink

The graphene/Ag nanowire conductive ink was prepared by dispersing graphene powder (2 wt%) and Ag nanowires (1 wt%, ~80 µm length, 50 - 100 nm diameter) in ethyl acetate containing 0.75 wt% CAB resin and 0.5 - 1 wt% dispersant. The mixture was mechanically stirred at 500–800 rpm for 30 min, ultrasonicated at 200 - 400 W for 30 min below 40 °C, and then bead-milled with zirconia beads at 1,500 - 2,000 rpm for 60 min to obtain a homogeneous ink with a viscosity of 1–5 Pa·s. The ink was degassed, screen-printed onto substrates, and dried and pressed at 80–120 °C for 30 min to form continuous conductive patterns.

Metamaterial absorber design on photo paper

The proposed graphene-based metamaterial absorber (GMA) is engineered to operate at 5.8 GHz and consists of a periodic arrangement of identical cross-shaped unit cells, as illustrated in Fig. 3(a). Each unit cell comprises three distinct layers: a bottom aluminum layer serving as the ground plane, a middle Kodak photo paper layer acting as a flexible dielectric substrate with thickness w_2 and length l_1, and a top

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conductive graphene layer patterned into a cross shape with dimensions w_1 and l_2.

Results and discussion

Figure 1 shows SEM images highlighting the morphology and dimensional parameters of graphene nanoplatelets (GNPs) and Ag nanowires (AgNWs).

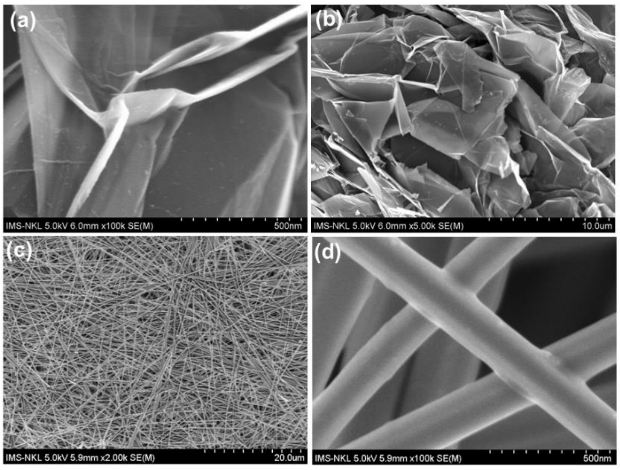

Fig 1. SEM images of (a,b) graphene nanoplatelets and (c,d) Ag nanowires

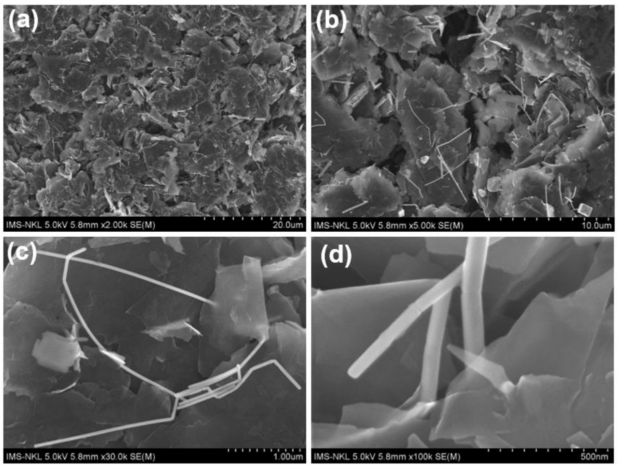

Fig 2. SEM images of graphene/Ag nanowires conductive ink at different resolutions

In panels (a) and (b), the GNPs display thin, crumpled, and overlapping sheet-like structures. Individual graphene sheets exhibit lateral dimensions on the order of several micrometers (≈5–20 μm), with thicknesses in the nanometer range, typically a few to tens of nanometers, consistent with few-layer graphene. The wrinkled edges and folded regions indicate high flexibility and large specific surface area, which favor interfacial contact and conductive network formation. Panels (c) and (d) present Ag nanowires forming a percolated network. The AgNWs show uniform diameters of approximately 50–100 nm and lengths ranging from several micrometers up to tens of micrometers, yielding very high aspect ratios (>100). At higher magnification, the smooth surface and continuous structure of individual nanowires are evident. Such geometric parameters enable efficient electron transport and low percolation thresholds. The combination of 2D GNPs and 1D AgNWs is therefore structurally favorable for synergistic electrical and functional performance.

Figure 2 shows SEM images of graphene/Ag nanowire conductive inks, revealing a well-integrated hybrid microstructure. Graphene sheets are uniformly distributed and act as a flexible, planar matrix, while Ag nanowires are embedded within and bridge adjacent graphene layers. The nanowires form continuous, interconnected pathways and effectively connect separated graphene domains, enhancing electrical percolation. Good interfacial contact between graphene nanoplatelets and Ag nanowires is evident, with no severe aggregation or phase separation observed. This intertwined 2D–1D network structure is favorable for charge transport, mechanical stability, and ink processability. Overall, the SEM results confirm the successful formation of a synergistic conductive network suitable for printed electronics applications. The fabricated graphene/Ag nanowire conductive ink has a line resistance of 42 Ω/cm.

Figure 3 illustrates the design, macroscopic patterning, and microscopic morphology of the ink-printed metamaterial absorber. In Figure 3(a), the unit cell geometry is shown as a cross-shaped resonator with well-defined dimensions (l_1 = 18 mm, l_2 = 15 mm, w_1 = 8 mm). This symmetric design is intended to support multiple resonant modes and polarization-insensitive electromagnetic absorption, while maintaining a compact footprint suitable for periodic array fabrication. Figure 3(b) presents an optical image of the patterned array printed on photo paper using graphene/Ag nanowire conductive ink. The unit cells are uniformly replicated over a large area with high pattern fidelity, sharp edges, and consistent spacing. This confirms good ink rheology, controlled spreading on the paper substrate, and reliable print resolution, which are critical for scalable and low-cost fabrication. Figure 3(c) shows the SEM image of the printed graphene/Ag nanowire layer on photo paper. The surface exhibits a rough, hierarchical microstructure where graphene flakes form a continuous matrix, while Ag nanowires are embedded and interconnect adjacent graphene domains. This interconnected 2D - 1D conductive network enhances electrical conductivity and electromagnetic loss. Overall, the results

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demonstrate successful integration of structural design and functional ink printing for flexible metamaterial absorber applications.

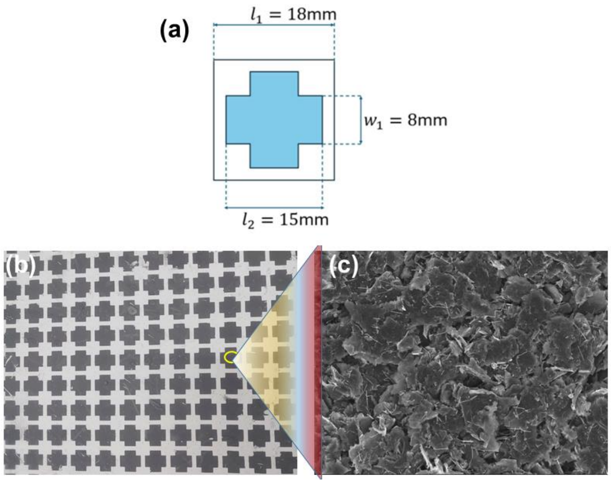

Fig 3. (a) Design of the metamaterial absorber unit cell, (b) optical image, and (c) SEM image of graphene/Ag nanowires ink-printed photo paper

Figure 4 illustrates the electromagnetic wave absorption performance of the graphene/Ag nanowire conductive ink printed on a paper substrate at an incident angle of 60°. The absorber maintains high absorption efficiency, reaching approximately 90–100% in the 2–8 GHz and 16–18 GHz ranges, while the minimum absorption remains around 25–35% near 11–13 GHz. Despite oblique incidence, the structure preserves strong absorption over a wide frequency range, confirming good angular stability. Slight resonance shifts and minor reductions in peak absorption are observed at 60°, which are expected due to changes in current distribution and electromagnetic field paths. The high absorption performance is attributed to the symmetric metamaterial design and effective impedance matching. Additionally, the graphene–Ag nanowire network enhances electrical conductivity and dielectric/ohmic losses, while the paper substrate provides lightweight and flexible properties. Overall, the absorber demonstrates robust wide-angle performance suitable for practical applications.

Figure 5 presents the simulated electromagnetic wave absorption efficiency of the graphene/Ag nanowire ink printed on a paper substrate at an incident angle of 60°. The results show that absorption increases from approximately 25–30% at 4 GHz to about 60–70% in the 8–12 GHz range, reaching a maximum of ~98–100% near 14–15 GHz. In the higher frequency region (16–18 GHz), the absorption remains high at ~85–95%, before dropping sharply to around 25–30% above 18 GHz. These results confirm strong absorption performance and good effectiveness of the metamaterial absorber under oblique incidence.

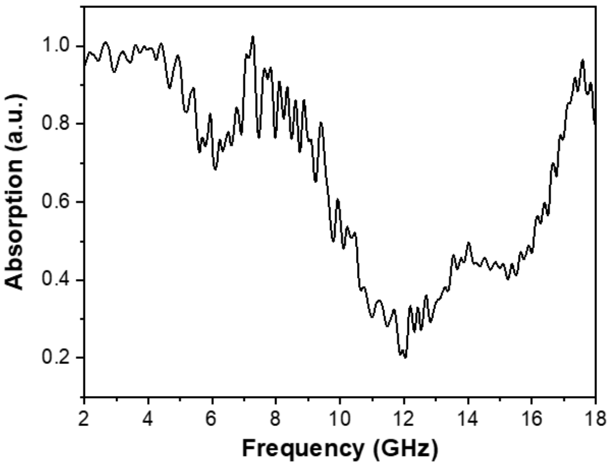

Fig 4. Electromagnetic wave absorption behavior by graphene/Ag nanowires conductive ink on paper substrate in angle of 60°.

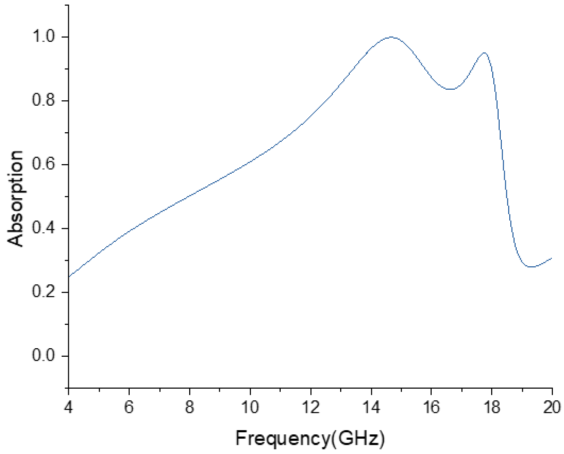

Fig 5. Simulation of Electromagnetic wave absorption efficiency by graphene/Ag nanowire ink on paper substrate in angle of 60°

The absorption peaks correspond to resonant modes generated by the cross-shaped unit cell, where strong surface currents and localized electromagnetic fields are induced. Minor frequency shifts and reduced peak intensity compared with normal incidence are observed due to angular-dependent field distribution. Nevertheless, effective impedance matching and enhanced conductive and dielectric losses from the graphene–Ag nanowire network ensure stable absorption performance, validating the experimental observations and design robustness.

Compared with previously reported EM absorbers, the graphene/Ag nanowire (AgNW) system in this work demonstrates enhanced performance through a synergistic 2D–1D conductive network. Pure graphene-based materials often suffer from poor impedance matching, while AgNW-only systems lack sufficient dielectric loss. In contrast, the hybrid structure simultaneously improves electrical conductivity and interfacial polarization, leading to strong attenuation and effective impedance matching. As a result, high absorption (~90–100%) is achieved over a broad frequency range and remains stable at oblique incidence (60°), outperforming many conventional absorbers limited to normal incidence. Moreover, unlike bulk composites, this study introduces a printable ink approach on flexible paper substrates, offering a scalable and low-cost strategy for practical EM wave absorption applications.

Conclusion

This work demonstrates a printable graphene/Ag nanowire conductive ink for flexible electromagnetic wave absorption using a metasurface design. Graphene nanoplatelets with lateral sizes of approximately 5–20 μm and Ag nanowires with diameters of 50–100 nm and lengths of several to tens of micrometers formed a continuous 2D–1D conductive network. The ink was successfully printed into a cross-shaped unit cell (l_1 = 18 mm, l_2 = 15 mm, w_1 = 8 mm) on a paper substrate with high pattern fidelity. Both experimental and simulated results confirmed strong absorption performance and angular stability at an incident angle of 60°. Effective impedance matching and enhanced dielectric and ohmic losses enabled robust absorption, highlighting the suitability of this low-cost, lightweight, and scalable approach for practical EMI shielding and EM wave absorbing applications.

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References

1. Z. Wei, Z. Li, D. Chen, J. Liang, J. Kong, Small Struct., 6(7) (2025) 2400615. https://doi.org/10.1002/sstr.202400615
2. A. Parveen, A. Irshad, M.N.U. Shah, A.U. Rahman, D. Tyagi, M. Alam, S. Ullah, J. Tao, Adv. Mater. Technol., 10(20) (2025) e00710. https://doi.org/10.1002/admt.202500710
3. Y. Duan, H. Guan, Microwave Absorbing Materials, Jenny Stanford Publishing, New York (2016).
4. Y. Xia, W. Gao, C. Gao, Adv. Funct. Mater., 32(42) (2022) 2204591. https://doi.org/10.1002/adfm.202204591
5. J. Ren, P. Shi, X. Zu, L. Ding, F. Liu, Y. Wang, W. Guo, Nanoscale, 17(22) (2025) 13622-13645. https://doi.org/10.1039/D5NR00925A
6. T.T. Le, H.H.T. Bui, A.K.P. Dinh, D.V. Van, Q.D. Ho, H.A.N. Thi, T.T. Nguyen, ChemistrySelect, 7(4) (2022) e202104249. https://doi.org/10.1002/slct.202104249
7. P.T.H. Nguyen, Q.H. Nguyen, S.T. Huynh, T.H. Mai, T.T. Nguyen, T.S. Bui, M.T. Le, D.D. La, J. Electron. Mater., 54 (2025) 3949-3956. https://doi.org/10.1007/s11664-025-11822-w
8. J. Wiklund, A. Karakoç, T. Palko, H. Yiğitler, K. Ruttik, R. Jäntti, J. Paltakari, J. Manuf. Mater. Process., 5(3) (2021) 89. https://doi.org/10.3390/jmmp5030089
9. X. Wu, Z. Zhou, Y. Wang, J. Li, Coatings, 10(9) (2020) 865. https://doi.org/10.3390/coatings10090865
10. N. Sharma, N.M. Nair, G. Nagasarvari, D. Ray, P. Swaminathan, Flex. Print. Electron., 7(1) (2022) 014009. https://doi.org/10.1088/2058-8585/ac53b4
11. D. Fu, R. Yang, Y. Wang, R. Wang, F. Hua, Adv. Mater. Technol., 7(11) (2022) 2200027. https://doi.org/10.1002/admt.202200027
12. D. Lee, H. Lee, Y. Ahn, Y. Lee, Carbon, 81 (2015) 439-446. https://doi.org/10.1016/j.carbon.2014.09.076