e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Metamaterial-Loaded Honeycomb Sandwich Structures for Microwave Absorption: A Comparative Review of Two Design Strategies

Rivandio Sitanggang[1,*], Sovian Aritongang[2], Hotma Renta[3], Rivilyo Sitanggang[4], Richard Panjaitan[5]

[*1,2,3,5] Department of Physics, Faculty of Mathematics and Military Natural Sciences, Universitas Pertahanan Republik Indonesia, Bogor, Indonesia

[4] Department of Mathematics, Faculty of Mathematics and Military Natural Sciences, Universitas Pertahanan Republik Indonesia, Bogor, Indonesia

Abstract

Microwave absorbing structures that remain lightweight, thin, and effective over a wide frequency range are increasingly needed for electromagnetic protection, camouflage, and related applications. This review compares two recent open-access studies that load metamaterial-type resonators into honeycomb sandwich structures: a phase-gradient metamaterial/honeycomb sandwich composite designed for the 1–2 GHz band, and a split-ring resonator-loaded honeycomb sandwich structure designed for broadband 2–18 GHz absorption. A structured qualitative comparison was performed on materials, fabrication routes, characterization methods, design parameters, and reported performance. In the first study, adding the phase-gradient layer lowered the averaged reflectivity of a 30 mm honeycomb composite from −5.16 dB to −10.59 dB at 1–2 GHz (a 5.43 dB improvement) with a metamaterial layer of only 0.19 kg/m², yet the benefit decreased as the dielectric loss of the honeycomb increased, which the authors attributed to coupling interference. In the second study, a lossy Ni-doped ZIF-67/epoxy split-ring metasurface combined with a 12 mm carbon black-coated honeycomb and a magnetic bottom panel kept reflection loss below −10 dB across 2–18 GHz for incidence angles up to 70° in both TE and TM modes. The two designs are complementary rather than directly comparable, because they differ in target band, test method, and performance metric. Matching the dielectric properties of the core to the resonator, and testing at oblique incidence, emerge as key design principles.

Keywords: Honeycomb Sandwich Structure, Metamaterial, Microwave Absorption, Split-Ring Resonator, Phase-Gradient Metasurface

Correspondent Author : Rivandio Sitanggang
E-mail : xsecondsecondx@gmail.com

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

1. Introduction

Microwave-absorbing materials are used wherever unwanted electromagnetic energy must be suppressed, including electromagnetic shielding, camouflage, and radar stealth (Qin and Brosseau, 2012; Cao et al., 2018; Jiang et al., 2019). Reviews have covered the theory of microwave absorption and recent absorber development (Zeng et al., 2020), carbon-based materials and their composites for electromagnetic interference shielding (Gupta and Tai, 2019; Wu et al., 2021), carbon nanostructures for high-frequency absorption (Li et al., 2019), and magnetic–dielectric microspheres (Wang et al., 2021). Absorber compositions range from ceramics and composites to carbon spheres, Fe-based composites with N-doped carbon, and magnetic Ni microspheres with core–shell structures (Yin et al., 2014; Chen et al., 2022; Liu et al., 2021; Zhang et al., 2022).

Among the available forms, structural absorbers are attractive because a single component can carry mechanical load and attenuate microwaves at the same time, as in glass/epoxy laminates containing carbon black and in two-layer periodic stepped structures (Oh et al., 2004; Zhou et al., 2017). Honeycomb sandwich composites are widely used in aeronautical structures and automobiles because they are light and have a high stiffness-to-mass ratio, and coating or filling their hexagonal cells with lossy agents turns them into efficient absorbers (Li et al., 2022; Panwar and Lee, 2019). Their combined electromagnetic and structural performance has long been studied (Smith and Scarpa, 2004). The absorption of a honeycomb sandwich depends on the structure of the core, including its thickness, cell size, and anisotropy (Li et al., 2020; Chen et al., 2019; Choi and Kim, 2015), and on the coating thickness and dielectric properties of the lossy agent (Liu et al., 2014; Pang et al., 2021; Zhou et al., 2015). Magnetic micropowder coatings, two-layer honeycomb sandwich absorbers, and honeycomb-like carbon aerogels have also been examined (He et al., 2007; Luo et al., 2019; Xu et al., 2021). Reviews of layered absorbing and shielding structures also point to a steady demand for designs that are thin, light, and broadband at once (Panwar and Lee, 2019).

The difficulty grows at low frequencies. Long wavelengths pass through thin absorbers with little loss, so good absorption normally requires a thick core, a high loading of lossy filler, or magnetic materials with high permeability, all of which add weight (Jia et al., 2018; Li et al., 2022). Low-frequency absorbers have been explored with activated carbon@Fe_3O_4 composites (Yin et al., 2018) and with a flexible device based on a voltage-boosting strategy (Lv et al., 2018). The classical relation between absorber thickness and attainable bandwidth described by Rozanov (2000) makes this trade-off explicit. New mechanisms are therefore needed if low-frequency absorption is to be achieved in a light structure.

Metamaterials offer a different route. Built from subwavelength resonant units, they can provide electromagnetic responses that natural materials do not (Sun et al., 2019), and metasurfaces allow full control of the amplitude, phase, and polarization of electromagnetic waves (Zhang et al., 2016). Metamaterial absorbers with very high absorptivity were demonstrated early on (Landy et al., 2008), and ultra-broadband designs followed (Ding et al., 2012). Phase-gradient metasurfaces, which build on the generalized laws of reflection and refraction (Yu et al., 2011; Sun et al., 2012), can additionally deflect reflected and

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

transmitted waves into unusual directions and have been used to reduce radar cross section (Li et al., 2014; Feng et al., 2018). Coding metamaterials extend this idea to digital and programmable control (Cui et al., 2014).

Combining such structures with honeycomb cores is still comparatively little explored. An early example is an 'H'-shaped three-dimensional metamaterial placed inside a honeycomb absorber, which Li et al. (2022) summarize as reaching a reflectivity below −5 dB over 2–18 GHz (Huang et al., 2015). Other examples include a perforated lightweight broadband metamaterial absorber based on a 3D-printed honeycomb (Ghosh and Lim, 2018), a reconfigurable honeycomb metamaterial absorber with stable response against the incident angle (Shabanpour et al., 2020), honeycomb cores embedded with conductive periodic patterned surfaces (Baek et al., 2022), and frequency-selective surfaces embedded in patterned honeycomb absorbers (He et al., 2021). Frequency-selective surfaces have also been combined with carbon nanopowder absorbers (Micheli et al., 2014) and with composite coatings (Liu et al., 2022), and flexible sandwich metamaterials based on cylindrical water resonators show ultra-broadband absorption (Zhou et al., 2022). Other work has treated structural and absorbing requirements together, for instance the evolutionary optimization of a honeycomb metastructure for mechanical resistance and broadband microwave absorption (Huang et al., 2021), and an effective-medium optimization strategy for honeycomb absorbers (Yadav and Panwar, 2022).

Two recent open-access studies illustrate contrasting ways of loading resonators into honeycomb sandwich structures. Li et al. (2022) introduced a phase-gradient metamaterial layer to improve absorption at 1–2 GHz, whereas Zhao et al. (2022) embedded a lossy split-ring metasurface to broaden the effective absorption bandwidth and to make it insensitive to polarization and incidence angle. Because the two works target different bands, use different test methods, and report different metrics, their findings are rarely read side by side. This article therefore (i) compares the design concepts, materials, fabrication routes, and characterization methods of the two studies, (ii) summarizes their reported performance and the mechanisms proposed by the authors, and (iii) identifies design principles, limitations, and open questions for metamaterial-loaded honeycomb absorbers.

2. Research Methods

This study is a qualitative, comparative literature review. Two peer-reviewed, open-access research articles published in 2022 were selected for in-depth comparison: Li et al. (2022) in Polymers and Zhao et al. (2022) in Coatings. Both are distributed under a Creative Commons Attribution (CC BY 4.0) license. The articles were included because each (i) reports a honeycomb sandwich structure that incorporates a metamaterial-type resonator layer, (ii) quantifies microwave absorption experimentally, and (iii) explains the design parameters that govern performance.

For each study, the following information was extracted: structural architecture, materials, fabrication route, characterization methods, design parameters examined, reported performance metrics, and the mechanisms proposed by the authors. The extracted information was organized into comparison tables and analyzed through narrative synthesis. Numerical values are reported exactly as given in the original articles. No data

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

were re-measured or re-analyzed, apart from simple arithmetic that is identified as such in the text.

Because the two studies differ in frequency range, test geometry, and performance metric, no pooled statistics or direct ranking were attempted. The comparison instead focuses on design logic, shared principles, and complementary strengths. Supporting literature was taken from the reference lists of the two articles and used only to provide context for the design concepts, materials, and measurement methods discussed.

3. Results and Discussion

a. Research result

Both studies place a resonant layer in the top panel of a carbon black-loaded honeycomb sandwich, but the physics invoked is different (Table 1). In the study of Li et al. (2022), the metamaterial layer consists of subwavelength open square metal rings arranged on the phase-gradient principle. These anisotropic units resonate at the working wavelength and impose a phase shift on the incident wave, so that a phase gradient develops across the surface and both the reflected and the transmitted waves are deflected from their normal directions. According to the authors, abnormal reflection redirects the reflected lobe and so reduces the radar cross section, while abnormal transmission lengthens the path of the wave inside the honeycomb. The effective core thickness becomes $d/\cos(\theta)$, where d is the physical thickness and θ is the refraction angle, so more loss accumulates without a thicker core.

Zhao et al. (2022) instead divided the work among three layers: a top panel carrying a split-ring metasurface to optimize absorption at 2–4 GHz, a carbon black-coated honeycomb core that provides loss over the whole band, and a bottom panel of Ni-doped ZIF-67/epoxy resin (ER) intended to improve absorption at 4–8 GHz. The split rings themselves are made from a lossy composite and not from a metal. The authors argue that the rings generate electromagnetic resonance at 2–4 GHz, while the discontinuous periodic pattern reduces impedance mismatch at 4–18 GHz.

Table 1. Overview of the two reviewed studies

Aspect	Li et al. (2022)	Zhao et al. (2022)
Journal	Polymers 14(7), 1424	Coatings 12(11), 1706
Structure	Metamaterial/honeycomb sandwich composite (MHSC)	Split-ring resonator-loaded honeycomb sandwich structure
Resonator concept	Subwavelength open square metal rings arranged as a phase-gradient metasurface	Split-ring metasurface made of lossy Ni-doped ZIF-67/epoxy resin (25 wt%)
Target band	1–2 GHz; also evaluated over 1–18 GHz	2–18 GHz; resonance tuned at 2–4 GHz
Main objective	Improve low-frequency absorption without a significant weight increase	Broaden the effective absorption bandwidth and reduce sensitivity to polarization and incidence angle
Approach	Experiments: free-space permittivity and NRL-arch reflectivity	Experiments, CST simulation, and transmission-line calculation

Source: compiled by the authors from Li et al. (2022) and Zhao et al. (2022).

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Table 2 and Figure 1 summarize how the two structures were built. Li et al. (2022) fabricated the metamaterial by sputtering copper onto a 10–15 μm poly(ether-ether-ketone) (PEEK) film and wet-etching the periodic units. The film was stacked with quartz fiber/bismaleimide (BMI) prepregs and co-cured in an autoclave, during which the PEEK film dissolves into the resin matrix and fuses with the skin, which the authors state prevents the mechanical penalty of a redundant film layer. Honeycomb cores were prepared by repeatedly dipping Nomex honeycomb in a carbon black/BMI dispersion, giving eight cores with increasing dielectric properties (1#–8#). Zhao et al. (2022) mixed Ni-doped ZIF-67 with epoxy resin in a high-speed mixer to obtain the split-ring pattern, embedded it in a SiO_2 fiber-reinforced epoxy top panel, dip-coated the honeycomb with a carbon black/epoxy solution containing 28 wt% carbon black, and bonded the three parts with a 0.2 mm adhesive film.

Table 2. Materials, fabrication, and key structural parameters

Component	Li et al. (2022)	Zhao et al. (2022)
Top skin or panel	Quartz fiber/BMI prepreg; 1 mm selected	SiO_2 fiber-reinforced epoxy resin (ER) top panel
Resonator layer	Cu sputtered on 10–15 μm PEEK film and wet-etched; co-cured into the skin	Ni-doped ZIF-67/ER (25 wt%) split rings, 0.25 mm thick, embedded in the top panel
Honeycomb core	Nomex dip-coated with carbon black/BMI; eight grades (1#–8#); 30 mm selected	Honeycomb dip-coated with carbon black/ER (28 wt% in solution); 12 mm selected
Bottom layer	Carbon fiber/BMI reflection skin	Ni-doped ZIF-67/ER panel, 2.5 mm
Bonding	J-116 epoxy film; 180 °C, 0.3 MPa, 2 h	Adhesive film, 0.2 mm thick
Skin curing	Autoclave: 180 °C for 3 h, then 200 °C for 5 h, at 0.7 MPa	Not reported

Source: compiled by the authors from Li et al. (2022) and Zhao et al. (2022).

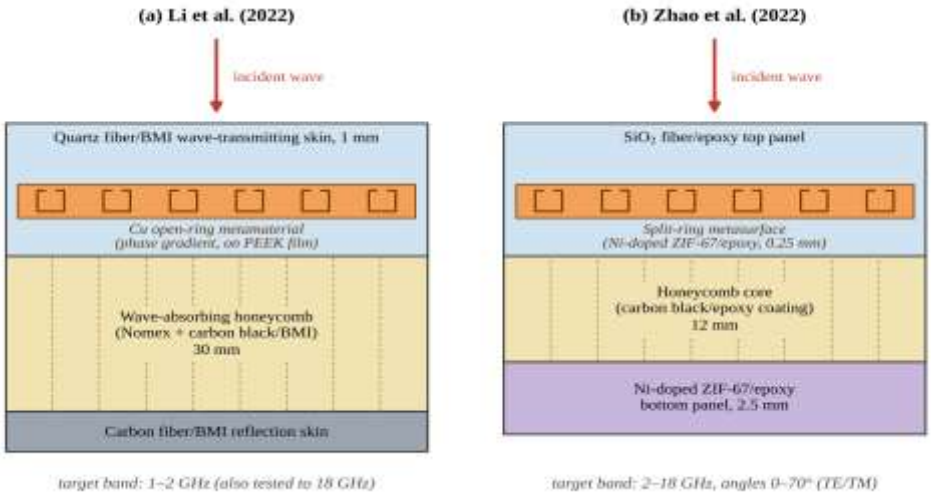


Figure 1. Layer architectures of (a) the phase-gradient metamaterial/honeycomb sandwich composite of Li et al. (2022) and (b) the split-ring resonator-loaded honeycomb sandwich structure of Zhao et al. (2022). Schematic prepared by the authors from the published descriptions; thicknesses are not to scale.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

The characterization strategies also differ. Li et al. (2022) measured the complex permittivity of the honeycomb in free space at 1–2 GHz using the Nicolson–Ross algorithm (Baker-Jarvis et al., 1990), and recorded reflectivity at normal incidence with the NRL-arch method on 600 mm × 600 mm samples, using a metal plate of the same size as the reference. Zhao et al. (2022) measured permittivity and permeability of the component materials with a vector network analyzer and rectangular waveguides at 2–18 GHz, measured reflection loss in a free-space arch system at different incidence angles and polarizations on 300 mm × 300 mm samples, and supported the experiments with CST Microwave Studio simulations and transmission-line calculations that assume a metal backplane (Miles et al., 1957; Naito and Suetake, 1971).

Li et al. (2022) first established the limits of conventional honeycomb sandwich composites (HSCs) without a metamaterial. Increasing the thickness of the wave-transmitting skin from 0.5 to 2.5 mm improved low-frequency absorption only slightly, and 1 mm was chosen as a compromise between absorption, weight, and mechanical properties. Raising the dielectric properties of the core improved absorption at first but then degraded it, because a large impedance mismatch at the skin–core interface reflects the incident wave. Even the best absorbing core (6#) left the reflectivity above −10 dB between 1 and 1.3 GHz, and cores with high dielectric properties are heavy, with surface densities from 1.8 to 9 kg/m² at 30 mm thickness (Table 3 lists the values for cores 1#–6#). Core thickness showed an optimum: for core 6#, thicknesses of 30 mm and 40 mm gave the lowest averaged reflectivity (−11.5 dB and −11.2 dB at 1–2 GHz), whereas 50 mm moved the resonant absorption peak below 1 GHz.

Table 3. Averaged reflectivity (R_a) at 1–2 GHz of conventional (HSC) and metamaterial-loaded (MHSC) composites with 30 mm cores

Core	Surface density at 30 mm (kg/m²)	$R_{a,HSC}$ (dB)	$R_{a,MHSC}$ (dB)	Reduction (dB)
Nomex (wave-transmitting)	n/r	0	−8.14	8.14
1#	1.8	−1.35	−7.85	6.50
2#	2.1	−2.80	−8.64	5.84
3#	2.4	−4.35	−10.18	5.83
4#	2.7	−5.16	−10.59	5.43
5#	3.0	−6.29	−10.38	4.09
6# (HSC only)	4.5	−11.5	n/r	–

Source: compiled from Li et al. (2022). n/r = not reported. Reduction = $R_{a,HSC} - R_{a,MHSC}$, expressed as a positive number of decibels. The R_a of HSC-6# is the averaged reflectivity given in the text of the original article.

Adding the metamaterial layer changed this picture (Table 3). With the wave-transmitting Nomex honeycomb alone, the layer lowered the averaged reflectivity by 8.14 dB, and with absorbing cores 1#–5# it produced reductions of 6.50, 5.84, 5.83, 5.43, and 4.09 dB, respectively. The best composite, MHSC-4#, reached an averaged reflectivity of −10.59 dB at 1–2 GHz against −5.16 dB for the matching HSC-4#, an improvement of 5.43 dB or more than 100%. The metamaterial layer has a surface

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

density of only 0.19 kg/m², much lower than that of the absorbing cores. Over a wider range, MHSC-4# showed an average of −11.18 dB at 1–4 GHz (−7.51 dB for HSC-4#), a −10 dB bandwidth of 5.4 GHz within 1–8 GHz (3.16 GHz for HSC-4#), and an average below −14.8 dB across 1–18 GHz with a minimum of −33.4 dB at 9.5 GHz. The abstract of the original article gives −14.6 dB for the 1–18 GHz average, so the two figures in that article differ slightly.

Zhao et al. (2022) optimized each layer in turn. For the carbon black-coated honeycomb, the imaginary part of the permittivity was close to the real part and both decreased with frequency, indicating pronounced dispersion. Calculated reflection loss showed that a core thickness of 10–14 mm gives optimal loss, and 12 mm was chosen because it matched impedance well at several frequencies; the shift of the peak to lower frequency with greater thickness was consistent with quarter-wavelength matching. The Ni-doped ZIF-67/epoxy bottom panel showed an imaginary permittivity much larger than the real part, indicating strong dielectric loss, and its imaginary permeability became negative between 10 and 18 GHz, which the authors explained through magnetic fields induced under high-frequency excitation. A thickness of 2.5 mm was selected for this panel after examining impedance and reflection loss for different thicknesses.

For the split-ring metasurface, thinner layers achieved impedance matching and attenuation more easily, and a thickness of 0.25 mm was chosen for fabrication feasibility. Simulated power-loss density showed that, in TE mode, loss concentrated near the ring gap at both 3 GHz and 14 GHz, where charge transport is interrupted and the accumulated charge is dissipated in the conductive region; the authors call this an interrupt-conduction phenomenon. In TM mode, loss was greatest in the ring segments parallel to the electric field. For the complete structure, the authors report reflection loss below −10 dB, equivalent to more than 90% absorption, across 2–18 GHz for incidence angles from 0° to 70° in both TE and TM modes, with a pronounced resonance near 3 GHz (Table 4).

Table 4. Reported performance of the two structures, as stated by the original authors

Metric	Li et al. (2022)	Zhao et al. (2022)
Reported metric	Averaged reflectivity (R_a); −10 dB bandwidth	Reflection loss (RL) below −10 dB; effective absorption bandwidth (EAB)
Low-frequency result	R_a = −10.59 dB at 1–2 GHz for MHSC-4# (HSC-4#: −5.16 dB)	Pronounced resonance near 3 GHz within the 2–4 GHz band
Wide-band result	Average below −14.8 dB over 1–18 GHz (−14.6 dB in the abstract); minimum −33.4 dB at 9.5 GHz	RL below −10 dB over the entire 2–18 GHz band
Incidence angle and polarization	Normal incidence only	0°–70°; TE and TM modes
Core thickness	30 mm	12 mm
Added mass of resonator layer	0.19 kg/m^2	Not reported

Source: compiled by the authors from Li et al. (2022) and Zhao et al. (2022).

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

b. Discussion

Taken together, the two studies show that resonant layers can be integrated into honeycomb sandwich structures following two largely different logics. In Li et al. (2022), the resonator is a metallic, low-loss pattern whose role is geometric: it manipulates the phase of the wavefront so that the lossy core is used more effectively and part of the reflected energy is redirected. In Zhao et al. (2022), the resonator is itself a lossy composite, so it contributes dissipation directly (Figure 1). The first approach is attractive when the aim is to add low-frequency performance to an existing core with almost no weight penalty, and the second when angular and polarization robustness over a broad band is the priority.

A central finding of Li et al. (2022) is that the benefit of the metamaterial depends on the core. The reduction in reflectivity fell steadily from 8.14 dB for the nearly lossless Nomex core to 4.09 dB for core 5# (Table 3), and the best absolute performance appeared at a moderate dielectric level (core 4#). The authors attribute this to coupling interference, whereby a more lossy core disturbs the electromagnetic response of the resonators. Zhao et al. (2022) raise the same concern in their introduction, noting that strong coupling between integrated absorbing structures may reduce the intrinsic absorption efficiency of each one, and their layered design co-optimizes the three layers through impedance analysis and makes the resonator itself lossy. Both papers therefore suggest that the resonator and the core should be designed as one system with matched dielectric properties, rather than by adding a metamaterial to the strongest available absorber.

Weight is the weak point of low-frequency absorbers, and the data of Li et al. (2022) allow a simple check. From the reported surface densities, the core and metamaterial layer of MHSC-4# amount to about 2.9 kg/m² (2.7 + 0.19), whereas HSC-6#, the best conventional core at the same 30 mm thickness, has 4.5 kg/m² and reached an averaged reflectivity of −11.5 dB. The metamaterial composite therefore reaches comparable low-frequency absorption (−10.59 dB) with roughly 1.6 kg/m² less core mass. This is our own arithmetic from reported values, it assumes the 1 mm skins are the same in both composites, and the two composites were not compared directly in the original article. In contrast, Zhao et al. (2022) use a much thinner core (12 mm) but do not report areal density, so the mass cost of their 2.5 mm Ni-doped bottom panel cannot be assessed.

Two cautions apply when interpreting the reported numbers. First, reflectivity measured in the specular direction at normal incidence falls both when energy is absorbed and when it is redirected elsewhere, and Li et al. (2022) invoke both effects. Without bistatic scattering data or absorptivity estimates, the share contributed by each cannot be separated. Second, the studies use different metrics and bands: Li et al. (2022) report band-averaged reflectivity from 1 GHz, and Zhao et al. (2022) report an effective absorption bandwidth defined by reflection loss below −10 dB from 2 GHz, so neither can be ranked above the other. Zhao et al. do not examine the 1–2 GHz band, and Li et al. describe measurements at normal incidence only.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Angular and polarization behavior is where the studies are most complementary. Zhao et al. (2022) attribute the insensitivity of their structure to incidence angle to the left-handed behavior that the split-ring metasurface acquires when the electric or magnetic field is perpendicular to it. They support this explanation with references to earlier work on the effective parameters of metamaterials and on the magnetic response of split-ring resonators (Smith et al., 2002; Koschny et al., 2003; Linden et al., 2004; Katsarakis et al., 2004) and with reflection-loss curves at different angles, and no effective-parameter retrieval is presented in the article. The phase-gradient units of Li et al. (2022) are described as anisotropic, so their dependence on polarization and incidence angle is an open question. It matters for curved surfaces, which Zhao et al. cite as the motivation for angular insensitivity, and which have also been addressed with reconfigurable frequency-selective surfaces (Zainud-Deen et al., 2020). Angular stability has likewise been pursued in honeycomb metamaterial absorbers (Shabanpour et al., 2020), and the oblique-incidence performance of radar-absorbing honeycombs has been examined directly (Feng et al., 2016).

Both studies concentrate on electromagnetic performance. Li et al. (2022) address mechanical aspects only indirectly, through the choice of a PEEK carrier film that dissolves into the skin resin, and Zhao et al. (2022) report no mechanical tests. Because honeycomb sandwich structures are load-bearing, flexural, compression, and interlaminar tests of metamaterial-loaded panels are needed before such designs can be adopted. The optimization of a honeycomb metastructure for mechanical resistance and broadband absorption by Huang et al. (2021) shows how both requirements can be treated together.

Several directions follow from this comparison. A hybrid design could combine a phase-gradient layer for low-frequency enhancement with lossy resonators for angular robustness, with the dielectric properties of the core tuned jointly with the resonator geometry. Optimization, for which effective-medium strategies already exist (Yadav and Panwar, 2022), should include areal density and mechanical performance as explicit objectives. Testing should cover oblique incidence, both polarizations, and bistatic scattering, and a common reporting format, for example averaged reflectivity and effective bandwidth over the same bands together with core thickness and areal density, would allow fair comparison across studies. This review is limited to two studies, relies on values as reported by their authors, and did not repeat any experiment. Its conclusions are therefore indicative and should be extended by a systematic search of the wider literature.

4. Conclusion

Based on the comparative review of Li et al. (2022) and Zhao et al. (2022), it can be concluded as follows. Both studies show that embedding a resonant layer can improve microwave absorption in a carbon black-loaded honeycomb sandwich structure, but with different aims: the phase-gradient composite targets 1–2 GHz, and the lossy split-ring structure targets broadband absorption at 2–18 GHz. In the phase-gradient design, the metamaterial layer lowered the averaged 1–2 GHz reflectivity from −5.16 dB to −10.59 dB (5.43 dB) with a layer of only 0.19 kg/m². The benefit declined as the dielectric loss of

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

the core increased, which the authors attribute to coupling interference, so resonator and core must be dielectrically matched. The lossy split-ring design kept reflection loss below −10 dB over 2–18 GHz for incidence angles up to 70° in TE and TM modes, which indicates angular and polarization robustness, although absorption below 2 GHz, areal density, and mechanical behavior were not addressed. The two designs are complementary rather than directly comparable. Future work should combine low-frequency enhancement with angular robustness, report weight and mechanical performance, and use common metrics so that metamaterial-loaded honeycomb absorbers can be compared fairly.

5. Compliance with ethical standards Acknowledgements

The authors thank the original authors of the two reviewed studies, which are open-access articles distributed under the Creative Commons Attribution (CC BY 4.0) license.

Disclosure of conflict of interest

The authors declare no conflict of interest.

Statement of informed consent

Not applicable. This article is a literature review and did not involve human participants.

References

Baek, S.M., Lee, W.J., Kim, S.Y. and Kim, S.S. (2022) 'A study on the microwave absorbing honeycomb core embedded with conductive periodic patterned surfaces for the effective dielectric constant', Composite Structures, 289, 115471. doi: 10.1016/j.compstruct.2022.115471.

Baker-Jarvis, J., Vanzura, E.J. and Kissick, W.A. (1990) 'Improved technique for determining complex permittivity with the transmission/reflection method', IEEE Transactions on Microwave Theory and Techniques, 38, pp. 1096–1103. doi: 10.1109/22.57336.

Cao, M., Han, C., Wang, X., Zhang, M., Zhang, Y., Shu, J., Yang, H., Fang, X. and Yuan, J. (2018) 'Graphene nanohybrids: excellent electromagnetic properties for the absorbing and shielding of electromagnetic waves', Journal of Materials Chemistry C, 6, pp. 4586–4602. doi: 10.1039/C7TC05869A.

Chen, H., Shen, R., Han, L., Zhou, Y., Li, F., Lu, H., Weng, X., Xie, J., Li, X. and Deng, L. (2019) 'Closed-form representation for equivalent electromagnetic parameters of biaxial anisotropic honeycomb absorbing materials', Materials Research Express, 6, 085804. doi: 10.1088/2053-1591/ab2020.

Chen, X., Wu, Y., Gu, W., Zhou, M. and Tang, S. (2022) 'Research progress on nanostructure design and composition regulation of carbon spheres for the microwave absorption', Carbon, 189, pp. 617–633. doi: 10.1016/j.carbon.2021.12.100.

Choi, W. and Kim, C. (2015) 'Broadband microwave-absorbing honeycomb structure with novel design concept', Composites Part B: Engineering, 83, pp. 14–20. doi: 10.1016/j.compositesb.2015.08.027.

Cui, T.J., Qi, M.Q., Wan, X., Zhao, J. and Cheng, Q. (2014) 'Coding metamaterials, digital metamaterials and programmable metamaterials', Light: Science & Applications, 3, e218. doi: 10.1038/lsa.2014.99.

Ding, F., Cui, Y., Ge, X., Jin, Y. and He, S. (2012) 'Ultra-broadband microwave metamaterial absorber', Applied Physics Letters, 100, 103506. doi: 10.1063/1.3692178.

Feng, J., Zhang, Y., Wang, P. and Fan, H. (2016) 'Oblique incidence performance of radar absorbing honeycombs', Composites Part B: Engineering, 99, pp. 465–471. doi: 10.1016/j.compositesb.2016.06.053.

Feng, M., Li, Y., Zheng, Q., Zhang, J., Han, Y., Wang, J., Chen, H., Sai, S., Ma, H. and Qu, S. (2018) 'Two-dimensional coding phase gradient metasurface for RCS reduction', Journal of Physics D: Applied Physics, 51, 375103. doi: 10.1088/1361-6463/aad5ad.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Ghosh, S. and Lim, S. (2018) 'Perforated lightweight broadband metamaterial absorber based on 3-D printed honeycomb', IEEE Antennas and Wireless Propagation Letters, 17, pp. 2379–2383. doi: 10.1109/LAWP.2018.2876023.

Gupta, S. and Tai, N. (2019) 'Carbon materials and their composites for electromagnetic interference shielding effectiveness in X-band', Carbon, 152, pp. 159–187. doi: 10.1016/j.carbon.2019.06.002.

He, F., Si, K., Zha, D., Li, R. and Jiang, J. (2021) 'Broadband microwave absorption properties of a frequency-selective surface embedded in a patterned honeycomb absorber', IEEE Transactions on Electromagnetic Compatibility, 63, pp. 1290–1294. doi: 10.1109/TEMC.2021.3050184.

He, Y., Gong, R., Cao, H., Wang, X. and Zheng, Y. (2007) 'Preparation and microwave absorption properties of metal magnetic micropowder-coated honeycomb sandwich structures', Smart Materials and Structures, 16, pp. 1501–1505. doi: 10.1088/0964-1726/16/5/001.

Huang, D., Kang, F., Zhou, Z., Cheng, H. and Ding, H. (2015) 'An "H"-shape three-dimensional meta-material used in honeycomb structure absorbing material', Applied Physics A: Materials Science & Processing, 118, pp. 1099–1106. doi: 10.1007/s00339-014-8922-1.

Huang, Y., Wu, D., Chen, M., Zhang, K. and Fang, D. (2021) 'Evolutionary optimization design of honeycomb metastructure with effective mechanical resistance and broadband microwave absorption', Carbon, 177, pp. 79–89. doi: 10.1016/j.carbon.2021.02.066.

Jia, Z.R., Lan, D., Lin, K.J., Qin, M., Kou, K.C., Wu, G.L. and Wu, H.J. (2018) 'Progress in low-frequency microwave absorbing materials', Journal of Materials Science: Materials in Electronics, 29, pp. 17122–17136. doi: 10.1007/s10854-018-9909-z.

Jiang, D., Murugadoss, V., Wang, Y., Lin, J., Ding, T., Wang, Z., Shao, Q., Wang, C., Liu, H., Lu, N. et al. (2019) 'Electromagnetic interference shielding polymers and nanocomposites – a review', Polymer Reviews, 59, pp. 280–337. doi: 10.1080/15583724.2018.1546737.

Katsarakis, N., Koschny, T., Kafesaki, M., Economou, E.N. and Soukoulis, C.M. (2004) 'Electric coupling to the magnetic resonance of split ring resonators', Applied Physics Letters, 84, pp. 2943–2945. doi: 10.1063/1.1695439.

Koschny, T., Markos, P., Smith, D.R. and Soukoulis, C.M. (2003) 'Resonant and antiresonant frequency dependence of the effective parameters of metamaterials', Physical Review E, 68, 065602. doi: 10.1103/PhysRevE.68.065602.

Landy, N.I., Sajuyigbe, S., Mock, J.J., Smith, D.R. and Padilla, W.J. (2008) 'Perfect metamaterial absorber', Physical Review Letters, 100, 207402. doi: 10.1103/PhysRevLett.100.207402.

Li, Q., Zhang, Z., Qi, L., Liao, Q., Kang, Z. and Zhang, Y. (2019) 'Toward the application of high frequency electromagnetic wave absorption by carbon nanostructures', Advanced Science, 6, 1801057. doi: 10.1002/advs.201801057.

Li, S., Huang, H., Wu, S., Wang, J., Lu, H. and Xing, L. (2022) 'Study on microwave absorption performance enhancement of metamaterial/honeycomb sandwich composites in the low frequency band', Polymers, 14(7), 1424. doi: 10.3390/polym14071424.

Li, W., Xu, L., Zhang, X., Gong, Y., Ying, Y., Yu, J., Zheng, J., Qiao, L. and Che, S. (2020) 'Investigating the effect of honeycomb structure composite on microwave absorption properties', Composites Communications, 19, pp. 182–188. doi: 10.1016/j.coco.2020.04.003.

Li, Y., Zhang, J., Qu, S., Wang, J., Chen, H., Xu, Z. and Zhang, A. (2014) 'Wideband radar cross section reduction using two-dimensional phase gradient metasurfaces', Applied Physics Letters, 104, 221110. doi: 10.1063/1.4881935.

Linden, S., Enkrich, C., Wegener, M., Zhou, J., Koschny, T. and Soukoulis, C.M. (2004) 'Magnetic response of metamaterials at 100 terahertz', Science, 306, pp. 1351–1353. doi: 10.1126/science.1105371.

Liu, L., Fan, C.Z., Zhu, N.B., Zhao, Z.Y. and Liu, R.P. (2014) 'Effective electromagnetic properties of honeycomb substrate coated with dielectric or magnetic layer', Applied Physics A, 116, pp. 901–905. doi: 10.1007/s00339-014-8458-4.

Liu, Q., Zeng, M. and Liu, J. (2021) 'Fe-based material@N-doped carbon composites as environment-friendly microwave absorbers', Carbon, 171, pp. 646–657. doi: 10.1016/j.carbon.2020.09.045.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Liu, Y., Yang, J. and Xu, J. (2022) 'Electromagnetic and microwave absorption properties of Ti3SiC2/AgNWs/acrylic acid resin composite coatings with FSS incorporation', Journal of Alloys and Compounds, 899, 163327. doi: 10.1016/j.jallcom.2021.163327.

Luo, H., Chen, F., Wang, X., Dai, W., Xiong, Y., Yang, J. and Gong, R. (2019) 'A novel two-layer honeycomb sandwich structure absorber with high-performance microwave absorption', Composites Part A: Applied Science and Manufacturing, 119, pp. 1–7. doi: 10.1016/j.compositesa.2019.01.015.

Lv, H., Yang, Z., Wang, P.L., Ji, G., Song, J., Zheng, L., Zeng, H. and Xu, Z.J. (2018) 'A voltage-boosting strategy enabling a low-frequency, flexible electromagnetic wave absorption device', Advanced Materials, 30, 1706343. doi: 10.1002/adma.201706343.

Micheli, D., Vricella, A., Pastore, R. and Marchetti, M. (2014) 'Synthesis and electromagnetic characterization of frequency selective radar absorbing materials using carbon nanopowders', Carbon, 77, pp. 756–774. doi: 10.1016/j.carbon.2014.05.080.

Miles, P.A., Westphal, W.B. and Von Hippel, A. (1957) 'Dielectric spectroscopy of ferromagnetic semiconductors', Reviews of Modern Physics, 29, pp. 279–307. doi: 10.1103/RevModPhys.29.279.

Naito, Y. and Suetake, K. (1971) 'Application of ferrite to electromagnetic wave absorber and its characteristics', IEEE Transactions on Microwave Theory and Techniques, 19, pp. 65–71. doi: 10.1109/TMTT.1971.1127446.

Oh, J., Oh, K., Kim, C. and Hong, C. (2004) 'Design of radar absorbing structures using glass/epoxy composite containing carbon black in X-band frequency ranges', Composites Part B: Engineering, 35, pp. 49–56. doi: 10.1016/j.compositesb.2003.08.011.

Pang, H., Duan, Y., Dai, X., Huang, L., Yang, X., Zhang, T. and Liu, X. (2021) 'The electromagnetic response of composition-regulated honeycomb structural materials used for broadband microwave absorption', Journal of Materials Science & Technology, 88, pp. 203–214. doi: 10.1016/j.jmst.2021.01.072.

Panwar, R. and Lee, J.R. (2019) 'Recent advances in thin and broadband layered microwave absorbing and shielding structures for commercial and defense applications', Functional Composites and Structures, 1, 032001. doi: 10.1088/2631-6331/ab2863.

Qin, F. and Brosseau, C. (2012) 'A review and analysis of microwave absorption in polymer composites filled with carbonaceous particles', Journal of Applied Physics, 111, 061301. doi: 10.1063/1.3688435.

Rozanov, K.N. (2000) 'Ultimate thickness to bandwidth ratio of radar absorbers', IEEE Transactions on Antennas and Propagation, 48, pp. 1230–1234. doi: 10.1109/8.884491.

Shabanpour, J., Beyraghi, S. and Oraizi, H. (2020) 'Reconfigurable honeycomb metamaterial absorber having incident angular stability', Scientific Reports, 10, 14920. doi: 10.1038/s41598-020-72105-4.

Smith, D.R., Schultz, S., Markos, P. and Soukoulis, C.M. (2002) 'Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients', Physical Review B, 65, 195104. doi: 10.1103/PhysRevB.65.195104.

Smith, F.C. and Scarpa, F. (2004) 'Design of honeycomb-like composites for electromagnetic and structural applications', IEE Proceedings – Science, Measurement and Technology, 151, pp. 9–15. doi: 10.1049/ip-smt:20030851.

Sun, S., He, Q., Hao, J., Xiao, S. and Zhou, L. (2019) 'Electromagnetic metasurfaces: physics and applications', Advances in Optics and Photonics, 11, pp. 380–479. doi: 10.1364/AOP.11.000380.

Sun, S., He, Q., Xiao, S., Xu, Q., Li, X. and Zhou, L. (2012) 'Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves', Nature Materials, 11, pp. 426–431. doi: 10.1038/nmat3292.

Wang, L., Li, X., Shi, X., Huang, M., Li, X., Zeng, Q. and Che, R. (2021) 'Recent progress of microwave absorption microspheres by magnetic–dielectric synergy', Nanoscale, 13, pp. 2136–2156. doi: 10.1039/D0NR06267G.

Wu, N., Hu, Q., Wei, R., Mai, X., Naik, N., Pan, D., Guo, Z. and Shi, Z. (2021) 'Review on the electromagnetic interference shielding properties of carbon based materials and their novel composites: recent progress, challenges and prospects', Carbon, 176, pp. 88–105. doi: 10.1016/j.carbon.2021.01.124.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License

e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Xu, J., Zhang, X., Zhao, Z., Hu, H., Li, B., Zhu, C., Zhang, X. and Chen, Y. (2021) 'Lightweight, fire-retardant, and anti-compressed honeycombed-like carbon aerogels for thermal management and high-efficiency electromagnetic absorbing properties', Small, 17, 2102032. doi: 10.1002/smll.202102032.

Yadav, R. and Panwar, R. (2022) 'Effective medium approximation fused optimization strategy derived new kind of honeycomb microwave absorbing structure', IEEE Transactions on Magnetics, 58, 2501311. doi: 10.1109/TMAG.2022.3140932.

Yin, P., Deng, Y., Zhang, L., Li, N., Feng, X., Wang, J. and Zhang, Y. (2018) 'Facile synthesis and microwave absorption investigation of activated carbon@Fe3O4 composites in the low frequency band', RSC Advances, 8, pp. 23048–23057. doi: 10.1039/C8RA04141E.

Yin, X., Kong, L., Zhang, L. and Cheng, L. (2014) 'Electromagnetic properties of Si-C-N based ceramics and composites', International Materials Reviews, 59, pp. 326–355. doi: 10.1179/1743280414Y.0000000037.

Yu, N., Genevet, P., Kats, M.A., Aieta, F., Tetienne, J., Capasso, F. and Gaburro, Z. (2011) 'Light propagation with phase discontinuities: generalized laws of reflection and refraction', Science, 334, pp. 333–337. doi: 10.1126/science.1210713.

Zainud-Deen, S.H., Malhat, H.A. and Shabayek, N.A. (2020) 'Reconfigurable RCS reduction from curved structures using plasma based FSS', Plasmonics, 15, pp. 341–350. doi: 10.1007/s11468-019-01048-y.

Zeng, X., Cheng, X., Yu, R. and Stucky, G.D. (2020) 'Electromagnetic microwave absorption theory and recent achievements in microwave absorbers', Carbon, 168, pp. 606–623. doi: 10.1016/j.carbon.2020.07.028.

Zhang, B., Mahariq, B. and Tran, N. (2022) 'Enhanced electromagnetic wave dissipation features of magnetic Ni microspheres by developing core-double shells structure', Ceramics International, 48, pp. 446–454. doi: 10.1016/j.ceramint.2021.09.120.

Zhang, L., Mei, S.T., Huang, K. and Qiu, C.W. (2016) 'Advances in full control of electromagnetic waves with metasurfaces', Advanced Optical Materials, 4, pp. 818–833. doi: 10.1002/adom.201500690.

Zhao, Y., Liu, Q., Xu, Z., Ji, G. and Mo, R. (2022) 'A split-ring resonator-loaded honeycomb sandwich structure for broadband microwave absorption', Coatings, 12(11), 1706. doi: 10.3390/coatings12111706.

Zhou, P.H., Huang, L.R., Xie, J.L., Liang, D.F., Lu, H.P. and Deng, L.J. (2015) 'Prediction of microwave absorption behavior of grading honeycomb composites based on effective permittivity formulas', IEEE Transactions on Antennas and Propagation, 63, pp. 3496–3501. doi: 10.1109/TAP.2015.2431721.

Zhou, Q., Xue, B., Sg, A., Gu, S., Ye, F. and Fan, X. (2022) 'Ultra broadband electromagnetic wave absorbing and scattering properties of flexible sandwich cylindrical water-based metamaterials', Results in Physics, 38, 105587. doi: 10.1016/j.rinp.2022.105587.

Zhou, Q., Yin, X., Ye, F., Liu, X., Cheng, L. and Zhang, L. (2017) 'A novel two-layer periodic stepped structure for effective broadband radar electromagnetic absorption', Materials & Design, 123, pp. 46–53. doi: 10.1016/j.matdes.2017.03.044.

International Journal of Health Sciences is licensed under a Creative Commons Attribution 4.0 International License