SCIENTIFIC JOURNAL OF FACULTY OF FINE ARTS ALEXANDRIA UNIVERSITY
PRINT ISSN : 2356-8038 ONLINE ISSN : 2535-227X
DOI : 10.21608/SJFA.2025.353597.1097

METAMATERIALS IN SUSTAINABLE BUILDING DESIGN: INVESTIGATING FABRICATION TECHNIQUES AND THEIR IMPACT ON INTERIOR SPACE EFFICIENCY

M. M. SALAMA[1], A.A. ALI (R.I.P)[2], S. M. Al Arnouty[3], H.S. Mohamed[4]

ABSTRACT

This research explores the integration of metamaterials in sustainable building design, focusing on advanced fabrication techniques and their impact on interior space efficiency. Metamaterials, with their unique properties, offer promising solutions for enhancing energy efficiency, thermal management, and acoustic performance in buildings.

The study investigates various fabrication methods, including additive manufacturing and laser processing, to create complex metamaterial structures. It assesses how these materials can improve lighting efficiency, reduce energy consumption, and enhance indoor environmental quality. Through a comprehensive analysis of existing literature and case studies, this research aims to provide insights into the potential benefits and challenges of incorporating metamaterials in sustainable interior design.

The findings contribute to the development of more efficient and sustainable building practices, aligning with global efforts to reduce environmental impact and promote sustainable development goals. This abstract highlight the core aspects of the research, including the focus on metamaterials, fabrication techniques, and their impact on sustainable interior spaces.

KEYWORD: Metamaterials, Sustainable Building Design, Fabrication Techniques, Additive Manufacturing, Laser Processing, Energy Efficiency, Thermal Management, Acoustic Performance, Interior Space Efficiency, Sustainable Development, Green Building Materials

1. INTRODUCTION

The built environment is a significant contributor to global energy consumption and environmental degradation, with buildings accounting for a substantial portion of greenhouse gas emissions and resource usage. In response to these challenges, sustainable building design has emerged as a critical area of focus, aiming to reduce the environmental impact of buildings while enhancing their functionality and efficiency.

One promising approach to achieving these goals is the integration of metamaterials into building design. Metamaterials are artificially engineered materials that exhibit unique properties not found in nature, such as tailored optical, thermal, and acoustic characteristics. These properties make metamaterials ideal for enhancing energy efficiency, improving thermal management, and optimizing acoustic performance in buildings.

[1] *Mariam Mohmed Salama Lecturer at the Faculty of Fine Arts, Alexandria University, Egypt, Décor Department.* Mariam.salama@alexu.edu.eg
[2] *Emeritus Professor of Interior Architecture, Department of Decoration Faculty of Fine Arts- Alexandria University*
[3] *Former Vice dean for post graduate studies and scientific research, Professor, Faculty of Fine Arts, Alexandria university.* drsahar_elarnaouty@yahoo.com
[4] *Professor and Head of the Decoration Department, Faculty of Fine Arts, Alexandria University.* Hanan.sobhy@alexu.edu.eg

Recent advancements in fabrication techniques, including additive manufacturing and laser processing, have made it possible to create complex metamaterial structures with precise control over their properties. However, the potential of metamaterials in sustainable building design remains largely untapped, with significant opportunities for innovation in interior space efficiency. This research aims to explore the fabrication techniques and applications of metamaterials in sustainable building design, with a focus on their impact on interior space efficiency. By investigating how metamaterials can be effectively integrated into building design, this study seeks to contribute to the development of more sustainable, efficient, and environmentally conscious built environments. By highlighting the importance of sustainable building design, the potential of metamaterials, and the focus of the fabrication techniques and interior space efficiency.

2. PROBLEM STATEMENT

Despite the growing emphasis on sustainable building practices, the built environment continues to face significant challenges related to energy efficiency, environmental impact, and indoor environmental quality. Traditional building materials often lack the necessary properties to optimize energy consumption, thermal management, and acoustic performance, leading to increased energy costs, environmental degradation, and compromised occupant comfort. The integration of metamaterials, with their unique properties, offers a promising solution to these challenges. However, several barriers hinder the widespread adoption of metamaterials in sustainable building design:

1. **Limited Scalability and Cost-Effectiveness**: Current fabrication techniques for metamaterials are often expensive and not scalable for large-scale building applications.
2. **Complexity in Design and Integration:** The design and integration of metamaterials into building systems require specialized expertise and infrastructure, which can be a significant obstacle for widespread adoption.
3. **Lack of Standardization and Regulation:** There is a need for standardized guidelines and regulations to ensure the consistent performance and safety of metamaterials in building applications.
4. **Insufficient Understanding of Long-Term Performance:** The long-term durability and performance of metamaterials in real-world building environments are not well understood, which raises concerns about their reliability and sustainability.

This research aims to address these challenges by investigating advanced fabrication techniques for metamaterials and assessing their impact on interior space efficiency. By exploring innovative fabrication methods and evaluating the performance of metamaterials in sustainable building design, this study seeks to provide insights into overcoming the current limitations and unlocking the full potential of metamaterials for creating more efficient, sustainable, and environmentally conscious built environments.

3. OBJECTIVES AND RESEARCH SCOPE

- **Research Objectives**:

1. To Investigate Advanced Fabrication Techniques for Metamaterials:
    - Identify and evaluate current and emerging fabrication methods (e.g., additive manufacturing, laser processing) for creating metamaterials with tailored properties.
    - Assess the scalability, cost-effectiveness, and environmental impact of these techniques.

2. To Assess the Impact of Metamaterials on Energy Efficiency in Buildings:
    - Analyze how metamaterials can enhance energy efficiency by improving thermal management, optimizing lighting systems, and reducing energy consumption.
    - Evaluate the potential of metamaterials in reducing greenhouse gas emissions and environmental footprint.
3. To Examine the Role of Metamaterials in Enhancing Indoor Environmental Quality:
    - Investigate how metamaterials can improve acoustic performance, air quality, and occupant comfort in interior spaces.
    - Assess the impact of metamaterials on occupant health and productivity.

- **This research focuses on:**
  Exploring the potential of metamaterials in enhancing the sustainability and efficiency of interior spaces within buildings. The scope includes:

1. Fabrication Techniques: Investigating advanced fabrication methods such as additive manufacturing and laser processing to create metamaterials with tailored properties.
2. Sustainable Building Design: Examining how metamaterials can contribute to sustainable building practices by improving energy efficiency, thermal management, and acoustic performance.
3. Interior Space Efficiency: Assessing the impact of metamaterials on enhancing occupant comfort, reducing energy consumption, and improving indoor environmental quality.

The research will draw on existing literature, case studies, and potentially experimental data to provide comprehensive insights into the role of metamaterials in sustainable building design.

- **Boundaries of the Research**

1. Geographical Scope: The study will focus on global trends and applications, with potential case studies from various regions.
2. Temporal Scope: The research will consider recent advancements in metamaterials and fabrication techniques, with a focus on future potential.
3. Disciplinary Scope: The study will intersect with materials science, architecture, engineering, and sustainability studies.

- **Exclusions**

1. Non-Metamaterial Technologies: The research will not delve into traditional building materials or technologies that do not involve metamaterials.
2. Exterior Building Envelope: While the focus is on interior spaces, exterior applications of metamaterials will not be the primary focus.

4. RESEARCH QUESTIONS

1. What are the most effective fabrication techniques for creating metamaterials with tailored properties for sustainable building applications?
2. How can metamaterials enhance energy efficiency in buildings, and what are the potential reductions in energy consumption and greenhouse gas emissions?
3. What impact do metamaterials have on indoor environmental quality, including acoustic performance, air quality, and occupant comfort?
4. What are the primary challenges and barriers to integrating metamaterials into sustainable building design, and how can they be addressed?

5. How can metamaterials be effectively integrated into building design to maximize their benefits while ensuring long-term durability and sustainability?
6. What are the long-term performance and sustainability implications of using metamaterials in building applications, and how can their end-of-life management be optimized?

These research questions provide a framework for exploring the potential of metamaterials in sustainable building design and addressing the challenges associated with their integration.

5. METHODOLOGIES

- **Research Approach**

Literature Review: Conduct a comprehensive review of existing literature on metamaterials, sustainable building design, and advanced fabrication techniques. This will provide a foundation for understanding current trends, challenges, and opportunities in the field.
Case Studies: Identify and analyze case studies of buildings that have incorporated metamaterials or similar advanced materials. This will help in understanding real-world applications and challenges.

- **Tools and Techniques**

Building Information Modeling (BIM): Utilize BIM software to simulate and analyze the integration of metamaterials into building designs, assessing their impact on energy efficiency and indoor environmental quality.
Life Cycle Assessment (LCA): Apply LCA tools to evaluate the environmental impact of metamaterials throughout their lifecycle, from production to end-of-life.
Deep Learning or Machine Learning: Consider using machine learning algorithms to predict the performance of metamaterials under different conditions or to optimize their design for specific applications.

- **Ethical Considerations**

Data Privacy: Ensure that all data collected from surveys or interviews is anonymized and handled in accordance with ethical guidelines.
Bias Avoidance: Strive to minimize bias in data collection and analysis by using diverse sources and methodologies.
Transparency: Maintain transparency in reporting methods and findings to ensure the research is reproducible and reliable.

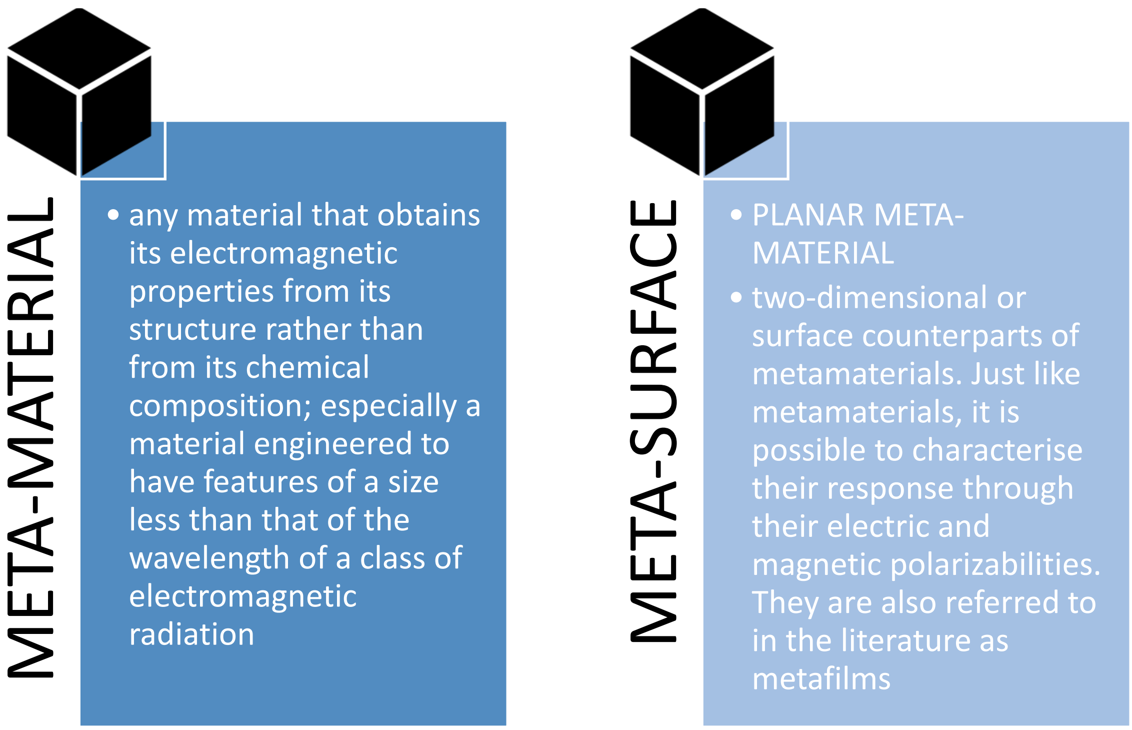
- **Limitations**

Access to Data: The availability of detailed case studies or primary data on metamaterials in building applications might be limited.
Technological Constraints: The complexity and cost of advanced fabrication techniques could limit the scope of experimental work.
Interdisciplinary Challenges: Integrating insights from materials science, architecture, and engineering might require collaboration across disciplines, which can be challenging.
By following this methodology, the research aims to provide a comprehensive understanding of how metamaterials can enhance sustainable building design and address the challenges associated with their integration.

6. DEFINING META-MATERIAL IN INTERIOR ARCHITECTURE FABRICATION

First and for most, The term Meta Greek origin which used to describe beyond, after or behind this prefix is used in English before any terms to designated the word as a higher level and outmost. (1) Metamaterials are artificially engineered materials designed to exhibit properties not found in naturally occurring substances. These properties arise from their unique structure rather than the intrinsic characteristics of their base materials. Typically, metamaterials are composed of subwavelength structures—elements smaller than the wavelength of the waves they interact with—arranged in specific, repeating patterns. This design enables them to manipulate electromagnetic, acoustic, or other physical waves in unconventional ways (1)

"*Meta-design is much more difficult than design; it's easier to draw something than to explain how to draw it.*" (2)



6.1 Key Characteristics of Metamaterials

Metamaterials have several distinctive features that set them apart:

- **Negative Refractive Index**: Certain metamaterials can bend light or other waves in the opposite direction compared to natural materials like glass or water. This negative refraction is one of their most notable properties.
- **Tailored Electromagnetic Properties**: They can be engineered to exhibit specific properties, such as negative magnetic permeability or electric permittivity, enabling precise control over wave interactions.
- **Subwavelength Structures**: The elements within metamaterials are smaller than the wavelength of the waves they influence, allowing for unprecedented control over wave behavior.
- **Homogenization**: The collective behavior of their sub-elements can be conceptualized as a continuous material with effective parameters, simplifying their design and application.

6.2 Applications of Metamaterials

Metamaterials have a wide range of applications across various fields:

- **Optics**: Development of super-lenses capable of imaging below the diffraction limit and invisibility cloaks that manipulate light to render objects invisible.
- **Acoustics**: Manipulation of sound waves for advanced noise control or seismic wave shielding
- **Energy Management**: Smart solar power systems and efficient energy harvesting devices.

Metamaterials represent a groundbreaking approach to material science, leveraging artificial structures to achieve extraordinary properties. Their potential lies in their ability to manipulate waves in ways not possible with conventional materials, opening doors to innovations in optics, acoustics, energy, and beyond.

Recently, Meta-material that has superior mechanical properties mechanical-meta-material that are classified as lab made material that have deviant nature properties, they are constructed from periodically tessellating units, The key concept behind of metamaterials is to scale up conventional continuum materials by using artificially designed and fabricated structural units.

In practice oriented, the research is constraining to a discipline process in the fields of study principally science and merging between the uses and the conceptual thinking in the interior architecture through material processing applied system.

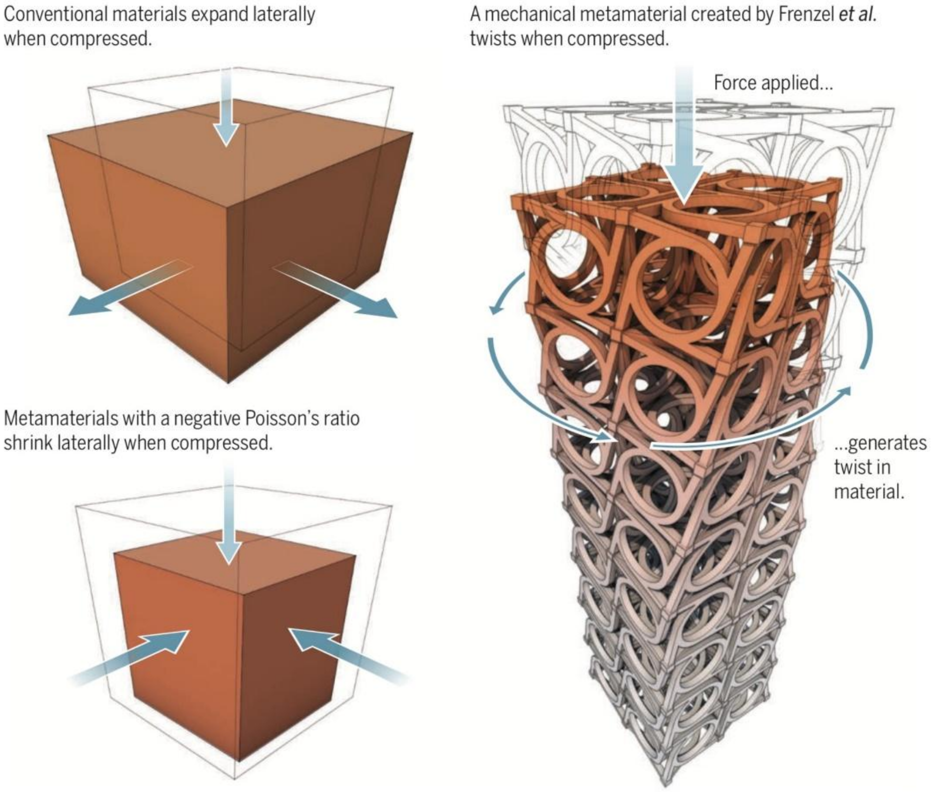


Figure 1 explaining the difference of normal material and material modified with Meta-technology generating a new behavior on the material source(3)

Metamaterials are poised to revolutionize interior architecture design and material fabrication by introducing multifunctional, adaptive, and energy-efficient solutions. Below is a detailed analysis of their impact, supported by recent research and industrial advancements:

6.3 Integration of Metamaterials in Interior Architecture

6.3.1 Smart Surfaces for Energy Management

Metasurfaces (2D metamaterials) can be spray-printed onto construction materials like plasterboard and wood, enabling energy harvesting from ambient microwave signals (4–7 GHz)1. These surfaces, integrated into walls, doors, or floors, can convert captured electromagnetic waves into electricity or optimize power usage in buildings. For example:

- Energy Harvesting: Metasurfaces with cut-wire designs generate electrical power from microwaves.
- Sensors: Split-ring resonator (SRR) metasurfaces monitor environmental changes (e.g., thermal fluctuations) for automated climate control.
- Photovoltaics is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect
- Electrochromic is a phenomenon in which a material displays changes in color or opacity in response to an electrical stimulus

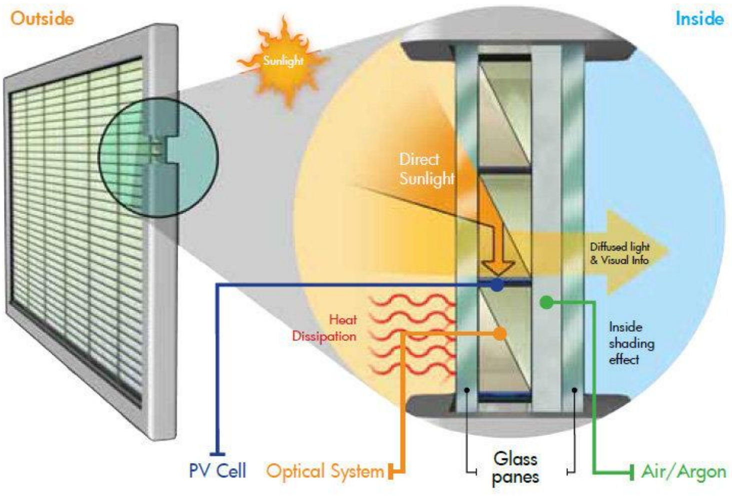


Figure 2 Integration of photovoltaic (PV) systems into window design (Photovoltaic Glass Unit pythagoras-solar.com).

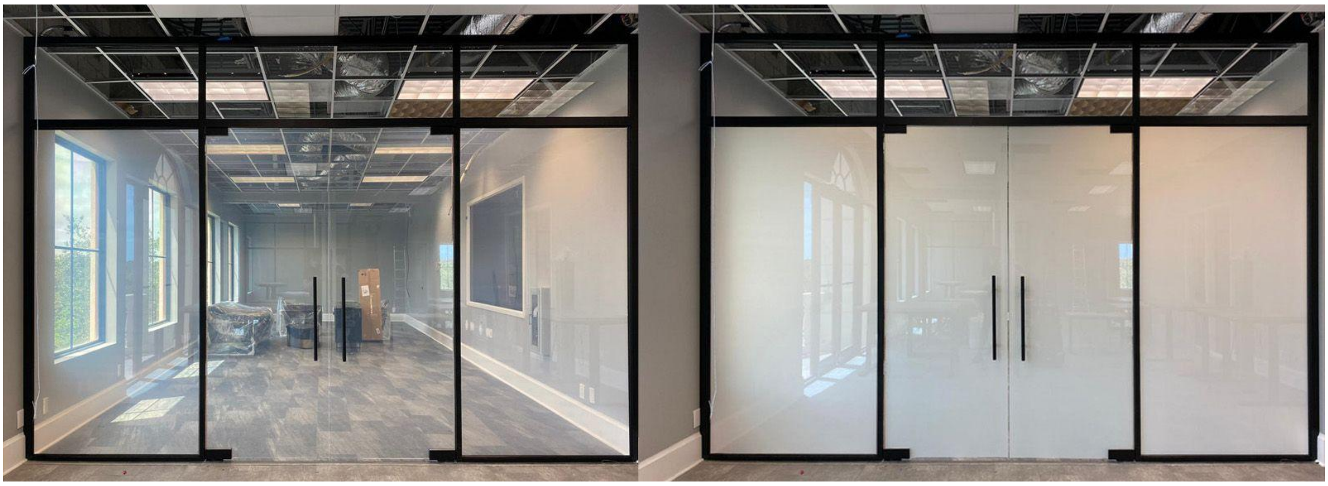


Figure 3 electrochromic glasses allow you to control the amount of light that passes through them, becoming transparent or opaque

6.3.2 Seismic and Acoustic Protection

- Seismic Metamaterials: Coatings that flex during earthquakes to dissipate seismic energy, enhancing building resilience.
- Acoustic Panels: Paper-thin metamaterials dampen sound waves, improving noise control in offices or residential spaces2. These can also convert vibrations into electrical energy for self-powered systems.

The Meta-material term is used often to mention the optical metamaterial as they create new optical characteristic that is not found in nature as (shown in table 1): (4)

Table 1 showing the type of the optical characteristic of the meta-material and surfaces

2.2.1 optical characteristic	Description
• **1.Quantum metamaterial:**	They are lab made materials engineered modified that are made up of quantum elements nanostructured. Furthermore, they are adjustable states of quantum maintain coherence of the elements in time higher than electromagnetic signal transversal time. (5)
• **2.Non-linear and amplifying metamaterial:**	Superior dynamic functionality by adding inducing local mechanism of inerta amplification in the repeated microstructure. It is mono-dimensional cellular lattice as characterized by pantograph mechanism to have minimal physical properties. (6)
• **3.Transformation optics:**	Transformation optics they are part of optical materials that is produced by using the application of metamaterial to make a spatial variation, this introducing new construction for a novel composite man-made device. That cannot be existed unless the presence of metamaterial and coordinate transformation. (7)
• **4.Invisible cloak:**	It applies on the reflection type meta-surfaces by merging the wave front tailoring properties applied on transparent metamaterial and the wave tunneling of zero index material creating a different type of hybrid invisible cloak that have a novel function in channeling geometry *(8)*
• **5.Slowing light:**	The new solution for the smoothing the time domain processing of optical signal. Introducing the chance for the spatial deflate of optical energy and enhancing all the optical effects. (9) These are called Photonics; the term is used to describe the novel optics solutions that use the meta-material and alternative electrodynamic phenomena to reach a modern optical effect. (10)

7. SOFT INTERIOR ARCHITECTURE SPACES THROUGH META-TECHNOLOGY ADJUSTING THE SUSTAINABLE INTERIOR SPACES

Designing a reconfigurable meta-material as a smart material with a diversity of functions, researchers at the Harvard SEAS[5] have designed a way of reconfigurable meta-material that can be reconstructed to different properties be reshaping and reorganizing from one form to a multiform that is adjusted to their own desired function. (11)
Soft interior architecture refers to the design and creation of flexible, adaptable, and often non-structural elements within interior spaces, such as partitions, curtains, and furniture. Meta-technology, involving advanced materials like metamaterials, can revolutionize these spaces by introducing unique properties that enhance sustainability and functionality.

7.1 Impact on Sustainable Interior Spaces

7.1.1 Energy Efficiency:
- **Thermal Management**: Metamaterials can be designed to manage heat transfer effectively, reducing the need for heating and cooling systems and thus lowering energy consumption.
- **Lighting Optimization**: By controlling light transmission and reflection, metamaterials can optimize natural lighting, reducing the reliance on artificial lighting sources.

7.1.2 Acoustic Performance:
- **Sound Absorption**: Metamaterials can be engineered to have superior sound absorption properties, improving acoustic comfort and reducing noise pollution in interior spaces.

7.1.3 Air Quality and Ventilation:
- **Air Filtration**: Incorporating metamaterials with enhanced filtration capabilities can improve indoor air quality by removing pollutants more effectively.

7.1.4 Sustainability and Durability:
- **Recyclability and Reusability**: Metamaterials can be designed to be recyclable or reusable, reducing waste and supporting sustainable design principles.
- **Long-Term Performance**: By ensuring that metamaterials maintain their properties over time, they can contribute to longer-lasting interior designs.

7.1.5 Adaptability and Flexibility:
- **Dynamic Spaces**: Metamaterials can enable the creation of dynamic, adaptive spaces that adjust to changing environmental conditions or user needs, enhancing the functionality and efficiency of interior spaces.

7.1.6 Challenges and Opportunities:

The high cost of production, limited scalability, and lack of standardization in metamaterials can hinder their widespread adoption in interior design. As technology advances, the potential for cost-effective, scalable production of metamaterials increases, offering opportunities for innovative, sustainable interior design solutions.

A Graduate school of Arts and Science (School of Engineer and Applied Science) in Harvard[5]

7.2 Material Fabrication Innovations

7.2.1 Additive Manufacturing (AM)

AM enables the production of complex, lightweight metamaterial geometries (e.g., lattice structures) at multiple scales. Examples include:

7.2.1.1 3D-Printed Metamaterials: Customizable acoustic panels or electromagnetic shields with tailored wave-manipulation properties.

7.2.1.2 Metal/Ceramic Composites: Durable metamaterials for load-bearing applications, such as reinforced walls or floors.

7.2.2 Scalable Fabrication Techniques

7.2.2.1 Spray Deposition: Compatible with standard construction practices, this method allows large-area Meta surface integration during building painting.

7.2.2.2 Fishnet Metamaterials: Advanced 3D stacking techniques enable large-scale production of optical/acoustic metamaterials for smart windows or privacy screens. (12)

8 THERMAL MANAGEMENT AND ENERGY EFFICIENCY FOR THE INTERIOR ARCHITECTURE FOR SUSTAINING THE INTERIOR SPACES

8.1 Thermal Regulation

Thermal metamaterials redirect heat flow through engineered structures, enabling dynamic insulation or heat redistribution. This reduces reliance on HVAC systems and improves energy efficiency.

During periods of low temperature, local field enhancement is employed to preferentially absorb energy in the near IR (infra-red) region of the sun spectrum.

The design calls for rotating the MTM window assembly to eliminate plasmon coupling in the near-infrared, producing performance comparable to that of conventional low-emissivity glass on a warm day with sunshine.

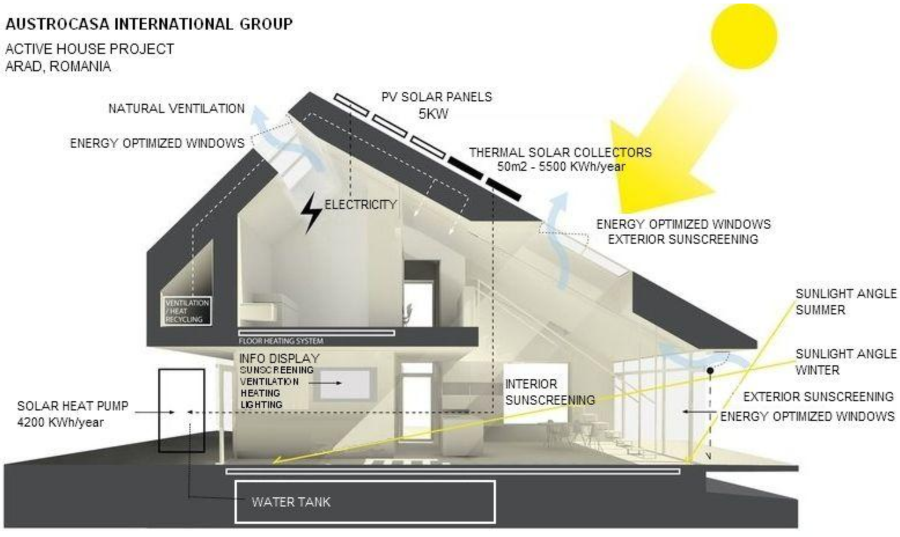


Figure 4 illustrate the comprehensive use of windows as a design feature as a poetic technique and a practical instrument to enhance quality of life in energy-efficient houses. Source : Hansen, Ellen & Arch, Cand & Maa,. (2023).

- By putting nanostructure metamaterials on the outside of the window, potential strategies for constructing transparent glass windows with ant frost/anti-fog and energy-saving characteristics will be investigated.
- When illuminated by light, the periodic metal-dielectric interfaces in the metal-dielectric-metal nanoscale metamaterial structures develop surface plasmons that trap light at subwavelength scales.
- These metamaterials may result in effective solar radiation absorption when coated on the outside of glass windows, which may be employed for anti-frost/anti-fog and energy-saving windows in contemporary buildings
- The metamaterial ideal solar absorber has an overall thickness of a few tens of nanometers, a wide, tunable absorption band, and is insensitive to the angle of incidence. (12)

8.2 Effective Heat Transfer:

Thermal Rectification: Metamaterials can be engineered to exhibit thermal rectification, allowing heat to flow preferentially in one direction. This property can be used to manage heat transfer within buildings, reducing the need for mechanical heating and cooling systems. (13)

Thermal Metamaterials: These materials can be designed with tunable thermal properties, enabling efficient heat flow control in various applications, including building insulation and thermal energy harvesting. (14)

In Figure 5 73% of incident sunlight is diffused by the metamaterial, making the inside more comfortable and private. The metamaterial's visible spectrum transmittance (95%) is higher than that of conventional glass (91%). In addition, compared to glass roofs, the metamaterial is thought to increase photosynthetic efficiency by about 9%. The metamaterial is thought to have a cooling capacity of about 97 W/m2 at room temperature, and its high emissivity (~0.98) is comparable to that of a mid-infrared black body. In humid Karlsruhe, the metamaterial was roughly 6 °C colder than the surrounding air. With a contact angle of 152°, which is much greater than that of glass (26°), the metamaterial demonstrates superhydrophobic performance and may have exceptional self-cleaning capabilities. As shown in figure (3)

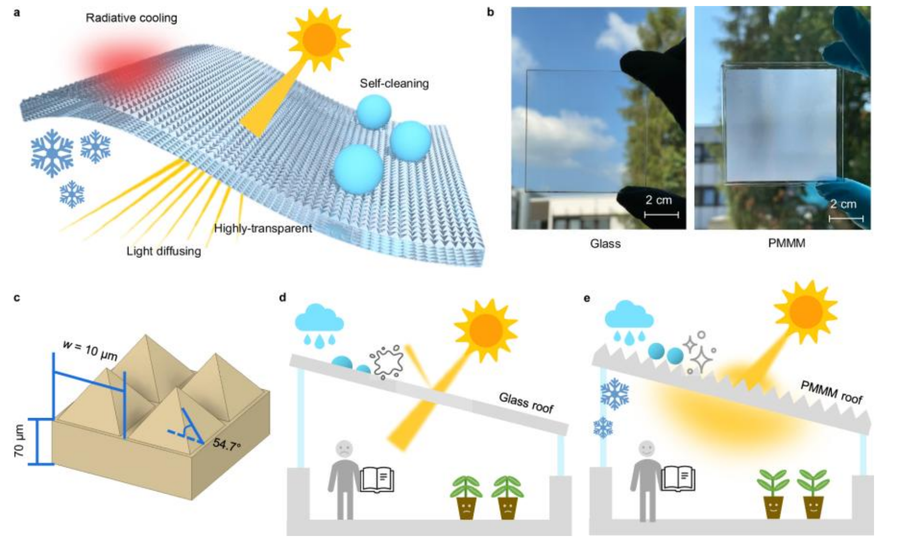


Figure 5 Figure 3 Huang, G., Yengannagari, A.R., Matsumori, K. et al. Radiative cooling and indoor light management enabled by a transparent and self-cleaning polymer-based metamaterial. Nat Commun ***15****, 3798 (2024). (15)*

8.3 <u>Radiative Cooling</u>:

<u>Infrared-Reflective Coatings:</u> Metamaterials can be used to create infrared-reflective coatings for windows, which reflect solar radiation while allowing visible light to pass through. This helps prevent overheating and reduces the need for air conditioning, enhancing energy efficiency(16)

9. ACOUSTIC PERFORMANCE ENHANCEMENT

9.1.<u>Sound Absorption:</u>

Low-Frequency Absorption: Metamaterials can be designed to absorb low-frequency sounds effectively, which is challenging with traditional materials (17)

Broadband Noise Reduction: Multi-layered micro-perforated metamaterials can achieve broadband noise reduction across low to mid-frequency ranges, making them suitable for applications in buildings and transportation. (18)

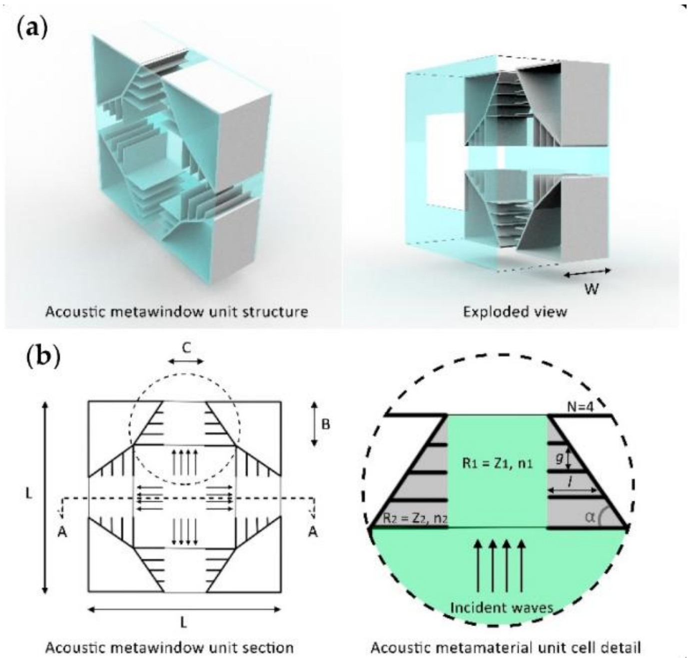


Figure 6 acoustic meta window unit structure image source: (19)

Acoustic Meta window (AMW) Unit Structure:

- ***Schematic Overview**: The AMW unit consists of a complex structure with specific geometrical parameters designed to optimize acoustic properties.*
- ***Dimensions and Components**:*
  - ***Unit Dimensions**: The unit has a width (W) of 0.13 meters and a length (L) of 0.4 meters.*
  - ***Ventilation Cavities**: The cavities have dimensions B = 0.095 meters and C = 0.067 meters.*
  - ***Space Cavities**: There are four cavities with lengths of 0.066, 0.05, 0.033, and 0.016 meters, each rotated at an angle (α) of 55 degrees.*
  - ***Channel Air Gap**: The distance between flanks is 0.024 meters.*
  - ***Purpose**: The AMW unit is analyzed numerically and experimentally to assess its acoustic performance, focusing on sound absorption.*

<u>9.2</u> <u>Noise Reduction:</u>

Space-Coiled Metamaterials: Innovations in space-coiled acoustic metamaterials, such as inclined perforated plate designs, enhance low-frequency absorption and improve coupling effects, leading to better noise reduction performance. (20)

<u>9.3 Acoustic Quality Improvement</u>:

Decorative Elements: Even traditional decorative elements like muqarnas in Turkish baths can influence acoustic quality. Metamaterials could be integrated into such designs to further enhance acoustic performance. (21)

<u>9.4Customizable Metamaterials:</u>

By tailoring the properties of metamaterials, they can be optimized for specific acoustic objectives, such as reducing reverberation time or improving speech clarity in interior spaces.

10 CONCLUSION

- By investigating advanced fabrication techniques and assessing the impact of metamaterials on energy efficiency, thermal management, and acoustic performance.
- The findings suggest that metamaterials can significantly contribute to reducing energy consumption and improving indoor environmental quality by optimizing thermal management, enhancing acoustic performance, and promoting sustainable design practices.
- However, challenges related to scalability, cost-effectiveness, and regulatory frameworks must be addressed to facilitate widespread adoption.
- This research contributes to the ongoing efforts to develop more sustainable and efficient built environments by highlighting the potential of metamaterials as a transformative technology. Future studies should focus on overcoming current limitations and exploring new applications of metamaterials in building design, ensuring that these innovative materials align with global sustainability goals and contribute to a more environmentally conscious future.
- This conclusion summarizes the main findings, highlights the potential of metamaterials in sustainable building design, and suggests future research directions to overcome current challenges and fully realize the benefits of these materials.

11 RECOMMENDATIONS

Integration of Metamaterials in Building Design:

Thermal Management: Incorporate metamaterials with tailored thermal properties to enhance building insulation and reduce heating and cooling needs.

Acoustic Performance: Use acoustic metamaterials to improve sound absorption and noise reduction in interior spaces, enhancing occupant comfort and productivity.

Sustainable Design Practices:

Green Building Principles: Adopt green building design principles that emphasize the use of eco-friendly materials, advanced ventilation systems, and biophilic design elements to improve indoor air quality and occupant experience

Solar-Optimized Design: Incorporate solar-optimized design strategies to maximize energy efficiency and reduce carbon emissions

Technological Innovation:

Artificial Intelligence (AI): Leverage AI to optimize building performance by analyzing environmental conditions, facilitating sustainable design processes, and improving material selection and construction efficiency

Regulatory Frameworks:

Sustainable Building Rating Tools: Develop and utilize government sustainable building rating tools that align with national priorities and encourage sustainable design practices in public buildings

Standards and Guidelines: Establish standardized guidelines for the integration of metamaterials into building design to ensure consistency and safety in their application.

Future Research Directions:

Scalability and Cost-Effectiveness: Investigate methods to improve the scalability and cost-effectiveness of metamaterial fabrication techniques.

Long-Term Performance: Conduct studies on the long-term durability and performance of metamaterials in real-world building environments.

12 REFERENCES

1. *Chaturvedi , Pratik & Hsu, Keng & Zhang, Shu & Fang, Nicholas. (2008). New Frontiers of Metamaterials: Design and Fabrication.*
2. *Donald Ervin Knuth (1986). "The META FONT book", Addison-Wesley Professional .*
3. *Corentin Coulais ,As the extension, so the twist.Science358,994-995(2017).DOI:10.1126/science.aaq0818*
4. *Zheludev NI (2010) The road ahead for metamaterials. Science*
5. *https://arxiv.org/abs/2006.03757*
6. *Andrea Bacigalupo, Nonlinear dispersion properties of one-dimensional mechanical metamaterials with inertia amplification, International Journal of Mechanical Sciences, Volume 201, 2021,*
7. *Pendry, Sir John (2006). "Transformation Optics". Imperial College, London. Retrieved 2010.*
8. *hu, H., Li, Q., Liu, B. et al. A hybrid invisibility cloak based on integration of transparent metasurfaces and zero-index materials. Light Sci Appl 7, 50 (2018)*
9. *Baba, T. Slow light in photonic crystals. Nature Photon 2, 465–473 (2008).*
10. *Reider GA (2016) Photonics, Springer*
11. *https://www.designboom.com/technology/harvard-crossfunctional-metamaterial-02-24-2017/*
12. *Tong, W.M., & Tong, A. (2015). Anti-frost and energy-saving transparent glass widows manipulated through solar-absorbing metamaterial coatings.*
13. *Meisam Askari, David A. Hutchins, Peter J. Thomas, Lorenzo Astolfi, Richard L. Watson, Meisam Abdi, Marco Ricci, Stefano Laureti, Luzhen Nie, Steven Freear, Ricky Wildman, Christopher Tuck, Matt Clarke, Emma Woods, Adam T. Clare,Additive manufacturing of metamaterials: A review, Additive Manufacturing, Volume 36,2020,101562, ISSN 2214-8604, https://doi.org/10.1016/j.addma.2020.101562. He, H., Peng, W., & Le Ferrand, H. (2024). Thermal Rectification in Modularly Designed Bulk Metamaterials. Advanced materials (Deerfield Beach, Fla.), 36(8), e2307071.*
14. *PHD thesis of M.M.S Hassan, the revitalization of the romen amphitheater of alexandria city through appling the metamaterial technology on the transparent reconstrected material, 2023*
15. *Huang, G., Yengannagari, A.R., Matsumori, K. et al. Radiative cooling and indoor light management enabled by a transparent and self-cleaning polymer-based metamaterial. Nat Commun 15, 3798 (2024).*
16. *Dede, E.M., Zhou, F., Schmalenberg, P., & Nomura, T. (2017). Thermal Metamaterials for Heat Flow Control in Electronics.*
17. *Jin, Y., Jeong, Y., & Yu, K. (2022). Infrared-Reflective Transparent Hyperbolic Metamaterials for Use in Radiative Cooling Windows. Advanced Functional Materials, 33.*
18. *Luo, Y., Yu, T., Kang, S., Zhang, D., Liu, S., Tian, X., & Sun, F. (2024). Analysis of Low-Frequency Sound Absorption Performance and Optimization of Structural Parameters for Acoustic Metamaterials for Spatial Double Helix Resonators. Crystals.*
19. *Maury, C., & Bravo, T. (2023). Vibrational Effects on the Acoustic Performance of Multi-Layered Micro-Perforated Metamaterials. Vibration.*
20. *Fusaro, G., Yu, X., Lu, Z., Cui, F., & Kang, J. (2021). A Metawindow with Optimised Acoustic and Ventilation Performance. Applied Sciences,11(7), 3168. https://doi.org/10.3390/app11073168*
21. *Liu, J., Wu, F., Li, T., Wang, J., Zou, X., & Zhang, D. (2024). Overcoming Bandwidth Limitations in Space-Coiled Acoustic Metamaterials through Inclined Perforated Plate Design. Chinese Physics B.*
22. *Agirbas, A., & Yildiz, E. (2023). The Effect of Muqarnas on Acoustic Quality of Traditional Turkish Bath Interior Space. ACM Journal on Computing and Cultural Heritage, 16, 1 - 20.*

SCIENTIFIC JOURNAL OF FACULTY OF FINE ARTS ALEXANDRIA UNIVERSITY
PRINT ISSN : 2356-8038 ONLINE ISSN : 2535-227X
DOI : 10.21608/SJFA.2025.353597.1097

خامه الميتا في التصميمات المستدامة: دراسة تقنيات التصنيع وتأثيرها على رفع كفاءة حيزات العماره الداخلية

م. م. سلامة [6] ، أ. أ. علي[7] ، (رحمه الله)، س. م. الأرناؤطي[8] ، ح. ص. محمد[9]

الملخص

تستكشف هذه الدراسة دمج الخامات الميتا في تصميم الفراغات المستدامة، مع التركيز على تقنيات التصنيع المتقدمة وتأثيرها على كفاءة الحيزات الداخلية . توفر الخامات الميتامادية، بخصائصها الفريدة، حلولاً واعدة لتحسين كفاءة الطاقة، وإدارة الحرارة،والأداء الصوتي في المباني.
تتناول الدراسة طرق التصنيع المختلفة، بما في ذلك التصنيع الإضافي والمعالجة بالليزر، لإنشاء هياكل ميتامادية معقدة. كما تقيّم كيف يمكن لهذه الخامات تحسين كفاءة الإضاءة، وتقليل استهلاك الطاقة، وتعزيز جودة البيئة الداخلية. من خلال تحليل شامل للأدبيات والدراسات الحالة الموجودة، تهدف هذه الدراسة إلى تقديم رؤى حول الفوائد المحتملة والتحديات المترتبة على دمج المواد الميتامادية في التصميم الداخلي المستدام.
تساهم النتائج في تطوير ممارسات بناء أكثر كفاءة واستدامة، بما يتماشى مع الجهود العالمية لتقليص الأثر البيئي وتعزيز أهداف التنمية المستدامة. يبرز هذا الملخص الجوانب الأساسية للدراسة، بما في ذلك التركيز على الخامات الميتامادية، وتقنيات التصنيع، وتأثيرها على المساحات الداخلية المستدامة.

الكلمات الدالة: الخامات الميتامادية، تصميم المباني المستدامة، تقنيات التصنيع، المعالجة بالليزر، كفاءة الطاقة، إدارة الحرارة، الأداء الصوتي، كفاءة الحيز الداخلي، التنمية المستدامة، مواد البناء الخضراء.

---

[6] مريم محمد سلامة، مدرس بكلية الفنون الجميلة، جامعة الإسكندرية، مصر، قسم الديكور.
Mariam.salama@alexu.edu.eg
[7] أستاذ العمارة الداخلية، قسم الديكور، كلية الفنون الجميلة، جامعة الإسكندرية. رحمه الله
[8] وكيل للدراسات العليا والبحوث العلمية السابق أستاذ العمارة بكلية الفنون الجميلة، جامعة الإسكندرية. drsahar_elarnaouty@yahoo.com
[9] أستاذ العمارة الداخلية ورئيس قسم الديكور، كلية الفنون الجميلة، جامعة الإسكندرية.
Hanan.sobhy@alexu.edu.eg