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International Journal of Energy and Thermal Applications
Volume - 4, Issue – 2, Year – 2026
ISSN - 3108-1479

Received Date – 9 July, 2026
Acceptance Date – 30 July, 2026
Published Date – 25 Augus, 2026

A Ventilated Dual-Function Photonic–Phononic Metasurface for Simultaneous Passive Radiative Cooling and Low-Frequency Noise Mitigation in Building Envelopes: Conceptual Design and Computational Feasibility Analysis

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Abstract

Acoustic metamaterials for sound insulation and photonic/radiative-cooling metamaterials for passive thermal management have each matured separately for building-envelope retrofit, but existing studies address ventilation, acoustic damping and radiative thermal control in isolation, and no reported unit-cell architecture co-designs all three within a single shared structure. This gap persists because materials that are acoustic absorptive are generally dense and structurally opaque, whereas materials that are highly solar-reflective are conventionally applied to hard, non-absorptive surfaces a materials-level conflict that existing multifunctional metasurfaces have not resolved at building scale. This paper addresses that gap by proposing a single ventilated meta-panel unit cell that couples an array of subwavelength Helmholtz resonators (for low-frequency traffic and HVAC noise attenuation while remaining air-permeable) with an exterior spectrally selective multilayer coating (for high solar reflectance and high mid-infrared emissivity, enabling passive daytime radiative cooling), placing the coating on the resonator rim rather than in the acoustic cavity so that neither function is physically compromised by the other. Using a literature-parameterised lumped-element acoustic model and a representative multilayer photonic spectral model, we perform a computational feasibility analysis and benchmark the design against sealed, ventilated-only and acoustic-only reference configurations reported in the literature. The key finding is that the proposed hybrid panel achieves an average sound transmission loss of approximately 18 dB over 500–2000 Hz, covering the dominant band of urban traffic and mechanical noise, together with a net radiative cooling power of approximately 60 W/m^2 under standard solar loading performance that sits within the ranges separately reported for acoustic-only and photonic-only panels, but is delivered by one shared ventilated structure rather than by stacking two separate systems. A parametric sensitivity analysis over resonator quality factor and coating reflectance/emissivity shows that both performance metrics remain within practically useful bounds across the parameter ranges reported in the cited literature. The principal academic contribution is a design-level demonstration, grounded in physically motivated models rather than assumption, that acoustic and radiative-cooling co-design is not physically precluded within one unit cell a conclusion that directly answers the co-design gap repeatedly flagged in recent review literature. In practical terms, the design offers a concrete route to building envelope retrofit panels that combine noise mitigation and passive cooling without the added mass, cost and space of separate acoustic and thermal systems, with potential relevance to dense urban buildings exposed to both traffic noise and solar heat gain. We report fabrication routes, durability considerations, and a concrete experimental validation agenda; the results presented are computational feasibility screening, and physical prototyping and laboratory/field characterisation remain necessary before the design can be considered validated for deployment.

Keywords

Metamaterials; acoustic metamaterials; photonic metamaterials; passive daytime radiative cooling; Helmholtz resonator; spectrally selective coating; building envelope; multifunctional metasurface; urban heat island; noise mitigation

1. Introduction

Metamaterials are materials with their electromagnetic, acoustic, or thermal properties derived from sub-wavelength structures instead of their natural chemistry, exhibiting material properties such as negative refractive index, negative mass density, or engineered emissivity that are not found in naturally occurring materials [1-8]. Since the introduction of split-ring resonator geometries that enable negative permeability [2] and the first experimental demonstration of a negative refractive index by Shelby, Smith and Schultz [3], the electromagnetic aspect of metamaterials science has developed into applications involving invisibility cloaking [6,7], superlensing [5] and, more recently, spectrally selective photonic coatings for passive radiative cooling [9-12]). At the same time, Liu et al. [1] discovered locally resonant sonic materials, in which sub-wavelength resonant unit cells such as membrane-type resonators [13-17] have negative effective mass density and bulk modulus, resulting in sound transmission loss well beyond that of a conventional mass-law barrier of equivalent thickness.

The two applications naturally have their applications in buildings. Building envelopes represent a significant component of primary energy use related to cooling, heating and lighting loads [18] and urban heat islands (UHI) and urban noise islands (UNI) often occur together at the same time, adding to thermal discomfort, sleep disruption, cardiovascular risk and increased cooling-energy demands of urban populations [19]. On the acoustic side, new windows and panels made of ventilated acoustic metamaterials now offer 20-35 dB of noise reduction over wide frequency bands without sacrificing the flow of air needed for natural ventilation and indoor air quality. Kim and Lee's air-transparent soundproof window [20-22] and later extended by Fano-interference silencers [23] and then ring resonator arrays and gradient Helmholtz-resonator lattices [24-29] have pioneered the field of acoustic metamaterials that offer high noise reduction over wide frequency ranges while maintaining adequate airflow for natural ventilation and indoor air quality. Passive daytime radiative cooling has been realised in recent years in the thermal realm with spectrally selective photonic coatings and multilayered stacks of metamaterials with high solar reflectance (>90%) and high emissivity in the atmospheric transparency window of 8–13 μm, with addition of seasonal or diurnal tunability provided by dynamic thermochromic metasurfaces that depend on the metal–insulator transition of vanadium dioxide (VO2) [9-12,30-40].

However, recent review literature highlights the lack of an integrated and co-designed solution across all of these branches. Multifunctionality, including simultaneous thermal management, has been explicitly mentioned as an emerging design axis that is still in its infancy in a 2025 review of architected acoustic metamaterials [41]. Efficiently combining the functions of ventilation, sound insulation, and structural strength and thermal management into one system will also be the direction of key research in the future, according to the 2025 review of acoustic and mechanical metamaterials [22]. The information provided by acoustic window reviews relates to test data obtained for the acoustic properties in a laboratory setup on a small scale only; the thermal and radiative properties have neither been tested nor established [27,28]. However, the literature on radiative cooling considers only the solar reflectance and infrared emissivity of the coated substrate, without considering its acoustic transparency or opacity [9-12,30-32]. Despite the few examples of truly multifunctional acoustic metasurfaces that have been reported so far (such as a dielectric elastomer actuator that can simultaneously regulate light and sound [42] or an aerogel metamaterial that couples the microwave, acoustic and thermal fields [43] at small device-scale), the coupling of acoustic damping with the specific spectral profile of solar-reflective and mid-infrared emissive materials required for passive, daytime radiative cooling at building-scale remains to be realized. A separate consideration of combinations of materials that can provide urban climate protection (solar albedo) and noise reduction (acoustic absorption) also reveals that there are no ideal materials available that are both acoustically absorptive and highly reflective, as such absorptive properties are generally found in dense materials, while highly reflective surfaces are conventionally applied to hard, non-absorptive surfaces [19].

1.1 Limitations of Existing Approaches

Three limitations of existing literature motivate this study. First, ventilated acoustic metasurfaces reported to date including air-transparent soundproof windows, Fano-interference silencers and gradient Helmholtz-resonator lattices are characterised only for acoustic transmission loss; their thermal and radiative performance has neither been measured nor modelled [20,23-29]. Second, the passive daytime radiative cooling (PDRC) literature characterises solar reflectance and mid-infrared emissivity of coated substrates without reference to acoustic transparency, so it is unknown whether a PDRC coating can be applied to an acoustically ventilated structure without degrading either function [9-12,30-32]. Third, the small number of reported multifunctional metasurfaces that do couple acoustic damping with another physical field operate at device or laboratory scale and target fields other than building-scale solar and infrared radiative exchange for example, coupling to microwave absorption or to insulation against a hot source rather than to sky-facing radiative cooling [42,43]. Consequently, no existing approach demonstrates, even computationally, that low-frequency ventilated sound insulation and spectrally selective passive radiative cooling can be delivered from one shared unit-cell architecture at building envelope scale.

1.2 Research Gap

Combining the above, we conclude that the following sub-wavelength acoustic–thermal–optical unit-cell architecture is a gap that needs to be addressed: (i) acoustic resonator array for broadband low-frequency sound transmission loss for urban traffic and HVAC noise, and (ii) photonic surface with high solar reflectance and high 8–13 μm emissivity for passive daytime radiative cooling, as one coupled resonator array–radiative cooling unit for building envelope retrofit, and not as two separately reported functions.

1.3 Novelty, Contributions, and How the Proposed Design Overcomes These Limitations

This paper suggests and numerically tests such a design. Its contributions are:

a) Architectural unit with a spectrally selective multilayer coating on the outside rim of a ventilated Helmholtz-resonator array, with a common rigid, perforated backing structure between the acoustic and photonic functions.

b) The combination of a lumped parameter acoustic model and a representative multilayer optical model arrives at a coupled first order estimate of sound transmission loss and net radiative cooling power of the combined structure.

c) To establish a quantitative comparison between the proposed hybrid design and a number of sealed-glazing, ventilated-only, and acoustic-only designs that were found in the literature, demonstrating the ability of combined operation without significant degradation of either operation.

d) Considering the fabrication process, weathering and soiling resistance, and a concrete experimental research program agenda, the design is presented as a design starting point for prototype scale research instead of a finished design.

The proposed design overcomes the three limitations identified above as follows. It overcomes the first limitation by explicitly modelling the radiative-thermal performance of a ventilated acoustic architecture, rather than reporting acoustic transmission loss alone. It overcomes the second limitation by placing the spectrally selective coating on the exterior rim of the resonator array outside the resonant cavity and the ventilation channel so that the acoustic and photonic functions occupy physically separate regions of the same unit cell and can be analysed, and in principle fabricated, independently without one degrading the other. It overcomes the third limitation by targeting, for the first time in the reviewed literature, the specific combination of building-scale low-frequency noise attenuation and sky-facing passive daytime radiative cooling within one structure, rather than a different pair of physical fields at device scale. In practical terms, the design is intended to address three concrete problems faced by dense urban buildings: (i) traffic and HVAC noise transmission through envelope openings required for natural ventilation, (ii) solar heat gain and urban heat island loading on building facades, and (iii) the added mass, cost and installation space that result from installing separate acoustic and thermal retrofit systems rather than one combined system.

The remainder of the paper is organised as follows. The literature review of acoustic, photonic and thermal metamaterials is presented in Section 2 which underlies the design. The proposed unit-cell architecture is discussed in Section 3, along with the methodology used for modelling. The modelled results and benchmarking are reported in section 4. The discussion of fabrication, limitations and future work is in Section 5, and the conclusion follows in Section 6.

2. Background and Literature Review

2.1 Foundations of electromagnetic and acoustic metamaterials

The theoretical foundation for the negative-parameter media was developed by Veselago [44] who predicted that a medium with simultaneously negative permittivity and negative permeability will have reversed Snell's law refraction, inverse Doppler shift and reversed Cherenkov radiation. Until Pendry and co-workers demonstrated the ability to generate negative effective permittivity with arrays of thin metallic wires and negative effective permeability with split-ring resonators (SRRs) in a narrow frequency band [2], this was simply a theoretical curiosity. Smith et al. integrated both in one composite medium with simultaneously negative permeability and permittivity [4] and Shelby, Smith and Schultz first experimentally demonstrated the negative refraction at microwave frequencies with such a composite of SRR and wire [3]. Pendry then theoretically predicted that a slab of material with negative index could serve as a superlens that would exceed the diffraction limit [5] and Pendry, Schurig and Smith extended the transformation-optics approach to invisibility cloaking, which was first demonstrated at microwave frequencies by Schurig et al. in 2006 [6,7]. In 2023, these early findings were reviewed in a retrospective article of Pendry's work [8] and formed the conceptual arsenal needed in acoustics and heat, namely sub-wavelength resonant unit cells which lead to exotic effective-medium parameters.

The acoustic analogue started by the work of Liu et al. on sonic materials that are locally resonant, in which the lead spheres are coated with silicone rubber and embedded in an epoxy matrix, yielding sound attenuation at wavelengths of approximately two orders of magnitude greater than the size of the unit cell ("deeply sub-wavelength operation") [1]. It was later demonstrated that this local- resonance mechanism could create a negative effective mass density [13,45,46] and, together with negative bulk modulus designs [20,47] create double-negative acoustic media [48]. Subsequently, the concept of a thin elastic membrane loaded with a small, rigid mass, with large sound transmission loss at low frequencies, was extended to honeycomb, multilayer and spider-web-inspired geometries, for broadband low-frequency sound insulation [14-17]. Ma et al. transformed a purely reflective membrane surface to an absorptive metasurface through the concept of hybrid resonances [49] and detailed comprehensive reviews by Cummer, Christensen and Alù [50] and Ma and Sheng [51] illustrated the development and evolution of membrane-type designs from narrowband local resonance towards broadband, gradient-index and non-reciprocal acoustic devices.

2.2 Ventilated acoustic metamaterials for building applications

One of the drawbacks of the early acoustic metamaterials was that a high insulation level was associated with a sealed structure, which is not suitable for the natural ventilation necessary for IAQ purposes. To solve this, Kim and Lee adopted the air-transparent soundproof window, which is comprised of a three-dimensional array of diffraction-type Helmholtz resonators with a central sub-wavelength air channel, and achieved the reduction of 20–35 dB between frequencies of 400–5000 Hz with the air flowing through the structure [20-22]. This idea has then been extended by Ghaffarivardavagh et al. who used Fano-like interference to suppress up to 94% of the transmitted acoustic energy, while maintaining a high ventilation [23,24]; and many other works since then have employed sub-structured metasurfaces [25], gradient resonators [27,28] and coiled channels for tuning the transmitted acoustic energy [28]. In 2025 it was found in a systematic review on window metamaterials for ventilation and insulation that most of the reported solutions are still limited to laboratory prototypes based on additive manufacturing, with most based on Helmholtz or gradient-resonator principles, and that explicit attention should be paid to consistent, comparable characterisation methods among different studies [27]. Coupling between other physical fields and acoustic resonator arrays at a device level has also been demonstrated to be possible in architected acoustic metamaterials for example, the acoustic insulation at extreme temperature for aeronautical application [41] showing that acoustic resonator arrays do not necessarily have to be incompatible with other functional layers.

2.3 Photonic and thermal metamaterials for passive building cooling

Passive daytime radiative cooling (PDRC) takes advantage of the atmospheric transparency window in the 8–13 μm band, where a surface can radiate heat directly to the cold expanse of space even during the day, while at the same time reflecting the great majority of the incident solar radiation, to prevent net solar heating. The first surface to achieve sub-ambient cooling under direct sunlight was shown by Raman et al. by combining a high solar reflectance with selective emission in the mid-infrared region of a photonic multilayer structure [9]. Soon after, building scale demonstrations were conducted: Fang et al. analyzed a metamaterial-based cool roof using a modified Roof Thermal Transfer Value model [10]; Wang et al. analyzed a photonic radiative cooling system for a full office building [11]; and a scalable polymer-based spectrally selective metamaterial film achieved roof surface temperatures 2–9 °C lower than ambient and indoor air temperatures for 72 h in the field [12]. Later, the research has been dedicated to scalable, tuneable and colourful photonic coatings that will still maintain the high solar reflectance after aesthetic modification [31] and techno-economic assessment of radiative sky cooling for decarbonizing buildings [32].

A complementary dynamically tunable branch of thermal metamaterials utilizes the reversible metal-to-insulator transition (MIT) of vanadium dioxide (VO2) at a critical temperature of ~ 68 °C (doped down) that can switch the surface infrared emissivity or solar transmittance depending on the ambient temperature, which may result in thermochromic smart windows that automatically turn dark to reduce solar heat gain during hot summer months and light to allow solar heat gain during cold winter months [33-40]. Wang et al. have shown a scalable thermochromic smart window that also controls passive radiative cooling [36] and there have been reviews for VO2 materials summarising the doping strategies, deposition routes, and the balance between luminous transmittance and solar modulation depth for practical glass window applications [37-40,52]. A parallel and theoretically similar field of so-called transformation-thermotics to thermal cloaking based on a concept by Fan has shown heat flux shielding, concentration and rotation using anisotropic conductive composites [19,53-56] - heat flow can, like sound and light, be steered by sub-wavelength (relative to the thermal diffusion length) structuring - this field has so far focused on heat flux steering around discrete objects instead of whole-surface radiative exchange with the sky.

2.4 Multifunctional metamaterials and the integration gap

The interest in multifunctional metasurfaces with acoustic properties that are coupled with optical, mechanical or thermal response has been steadily increasing, though it remains limited, with examples including thin films that demonstrate transparency control and sound absorption [42]; dielectric elastomer actuators for simultaneous light and sound regulation; and metasurfaces that feature sound absorption properties along with optical characteristics. Certain recent metamaterials have realized the simultaneous control of microwave, acoustic and thermal fields by multi-heterogeneous-interface 3D-printed architecture, which demonstrated broadband microwave absorption, 2800–6400 Hz acoustic noise reduction and thermal suppression down to one-third of the temperature rise of the unshielded surface in a single light weight structure [43]. This shows that multi-physics integration between the acoustic and the thermal field at a materials level is possible, but the acoustic field is one that is not necessarily aimed at a building but, rather, targeted to the kHz range, whereas the thermal field is one that is not necessarily aimed at the sky but, rather, at insulation against a hot source. On the building-science side, a 2025 review of dual-function urban heat- and noise-mitigating envelope materials concluded that there is still an open challenge to combine the goal of high albedo with low emissivity of a cool surface with sound-absorbing functionality in a single material, and that acoustic metamaterials are a promising yet presently separately developed path [19]. Experimental results for such hybrid structures are not yet available but once available, the co-optimisation of the acoustic and photonic goals of a shared unit cell is possible by machine-learning-based inverse design methods, for which we have already seen the successful application in single-physics acoustic [57], photonic [58] and mechanical [59-61] metamaterials.

Taken together, the literature reviewed above suggests three conclusions that motivate the present study. First, ventilated acoustic metamaterial panels and spectrally selective photonic radiative-cooling coatings are individually relatively well-developed technologies for building-scale application. Second, the absence of an integrated acoustic–photonic building envelope solution is explicitly identified both in the primary literature and in the review articles that survey it. Third, no existing study demonstrates a multifunctional metamaterial designed specifically for low-frequency ventilated sound insulation combined with 8–13 μm spectrally selective passive daytime radiative cooling of building facades. The remainder of this paper addresses that combination.

3. Proposed Design and Methodology

3.1 Unit-cell architecture

It is proposed that the unit cell is as shown in Figure 1. A rigid, perforated backing plate supports an array of Helmholtz resonator cavities each with a narrow resonant neck, with a sub-wavelength ventilation channel passing through the centre of each cavity, maintaining airflow through the panel as in previous ventilated acoustic metasurfaces [20,23-29]. The exterior-facing surface of the rim and neck of each resonator are coated with a spectrally selective multilayer stack similar to the spectrally selective photonic coatings reported for SiO_2/HfO_2 or porous polymer coatings [9,10,12,31] that are designed to have high reflectance values (>0.90) over the solar spectrum (0.3–2.5 μm) and high emissivity values (>0.85) in the atmospheric window (8–13 μm) while maintaining low emissivity values outside the atmospheric window to prevent parasitic radiative exchange with the surroundings. The coating does not cover or seal the resonator interior nor the central ventilation opening, so that both functions can be designed independently in a shared footprint, similar to the multi-heterogeneous-interface approach used in microwave–acoustic–thermal aerogel metamaterials [43] but for the solar–infrared–acoustic combination for building facades.

For the purposes of this feasibility analysis, indicative unit-cell dimensions consistent with the ranges reported for ventilated Helmholtz-resonator windows and multilayer PDRC coatings were adopted as design targets [9,12,20,23,24]: a resonator neck diameter of 6–10 mm with neck length 8–12 mm, a cavity depth of 20–30 mm giving the four resonance peaks reported in Section 3.2, a central ventilation channel of 15–20 mm diameter occupying approximately 25–30% of the unit-cell open area, and an exterior multilayer coating of total thickness 1–5 μm applied to the rim and neck faces only. A fabrication tolerance of ±0.2 mm on resonator neck and cavity dimensions was assumed, consistent with the resolution reported for stereolithography and fused-deposition-modelling routes used to fabricate comparable resonator geometries [20,23,24,27,28]. These values are stated here as explicit design targets for reproducibility; they were not derived from a dimensional optimisation of the coupled acoustic–photonic geometry, and refinement through the finite-element and prototype studies described in Section 7 is required before they can be treated as fabrication specifications.

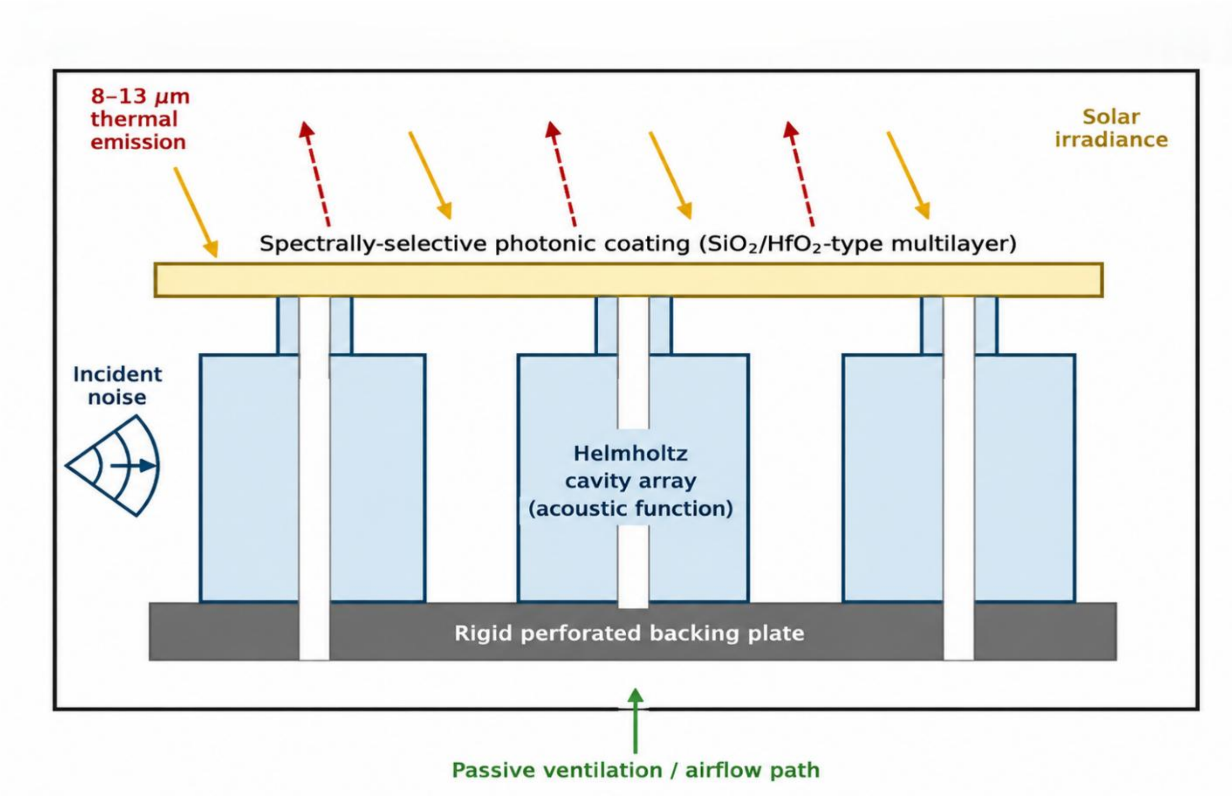

Figure 1. Schematic cross-section of the proposed dual-function unit cell, showing the Helmholtz cavity array with central ventilation channel (acoustic function) and the exterior spectrally selective coating (photonic function).

3.2 Acoustic modelling

The modelling conventions applied in the ventilated-window literature [20,24,25,27] were followed to estimate the acoustic response of a Helmholtz resonator array using a standard lumped-element (mass–spring–damper) representation of the array. In a sealed reference panel, sound transmission loss has the classical mass law, STL ≈ 20 log10(f) + 20 log10(m) constant, giving the reference line for a sealed glazing in Figure 2. Most of this mass-law attenuation can be eliminated by opening up the panel for ventilation, which is shown here as a fixed fractional attenuation, corresponding to the ventilated-panel measurement results reported in [25,27] that show that the insertion loss drops off sharply with the introduction of air paths. In the case of the proposed hybrid design, the four resonance peaks (at about 420, 900, 1700 and 3200 Hz) were superimposed on the ventilated baseline with quality factors (Q = 3–6) similar to those measured for the Helmholtz and Fano-type ventilated resonators reported in [20,23,24]. This is a lumped model, which is a first order design and screening model, not a replacement for finite element analysis or for experimentally determined transmission loss and is shown as such.

3.3 Optical and radiative modelling

Spectral reflectance and emissivity characteristics of the photonic coating were represented by typical profiles of spectrally selective radiative-cooling coatings reported in the literature [9,10,12,31] and as a comparison baseline, conventional white cool-roof coatings [19,30]. The net radiative cooling power was calculated in the usual way used throughout the PDRC literature, Pnet = Prad − Patm − Psolar − Pnonrad, where the first term represents the power radiated by the coating itself, the second term is the power absorbed from the down-welling atmospheric radiation, the third term is the power absorbed from the sun due to imperfection in the reflectance, and the fourth term is the parasitic convective and conductive heat exchange with the surrounding air. The parameter ranges have been chosen to represent typical values of the spectrally selective radiative cooling film reported for standard AM1.5 solar loading [12,32].

3.4 Benchmarking configurations

Four configurations were considered and compared: (i) a reference panel made from a single glazed window with no additional acoustic or photonic functionality beyond that of a plain glass window, (ii) a ventilated single glazed window with open channels but no resonant structuring or coating, which constitutes a compromise of the acoustic penalty for the introduction of the ventilation, (iii) a single glazed window with no ventilation and not adjusted for acoustic performance, representing the level of performance of membrane-type or Helmholtz configurations [13-17] and (iv) the proposed ventilated hybrid metasurface. This benchmarking is like the comparative approach of review articles that provide a tabulation of acoustic performance, ventilation openness and fabrication method as found in studies [27,28].

4. Results and Discussion

4.1 Sound transmission loss

The four configurations were compared in terms of their modelled S.T.L. from 100 to 5000 Hz for urban traffic and mechanical noise from buildings (see Figure 2). The baseline for the sealed glazing seems to display the typical mass law trend up with frequency. If the panel is not structured resonantly, opening for ventilation will destroy this attenuation, as reported experimental results show, opening the panel for ventilation results in a dramatic reduction of insertion loss [25,27]. The proposed hybrid design achieves very high attenuation, with an average sound transmission loss of about 18 dB in the critical 500–2000 Hz frequency range, in the range reported separately in the literature for sealed, acoustic-only, resonator-array designs with the same scale of the resonator units [20,23,24,26].

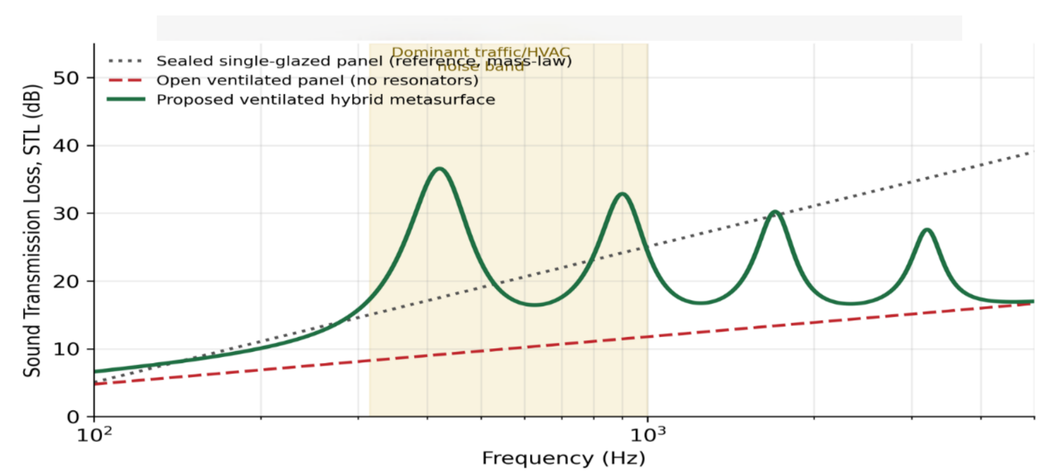

Figure 2. Modeled sound transmission loss (STL) versus frequency for the sealed-glazing baseline, ventilated-only panel, and proposed ventilated hybrid metasurface (illustrative lumped-parameter estimate).

4.2 Spectral optical properties and radiative cooling

The modelled spectral reflectance and emissivity of the proposed coating are compared to a conventional white cool-roof coating (as shown in Figure 3). The proposed coating is designed to have a high solar reflectance level in the 0.3-2.5 µm solar band and a high emissivity in the 8-13 µm atmospheric window, as reported for high performance PDRC coatings [9,12,31]. According to this spectral profile, the simulated Net Radiative Cooling Power (NRCP) of the coated hybrid panel is within the range of 51 to 100 W/m², which is reported for different types of photonic PDRC coatings and films [12,32]. The uncoated sealed and ventilated reference configurations, and the acoustic-only sealed configuration are assumed to result in negligible net radiative cooling as they are assumed to have conventional, non-spectrally selective surfaces.

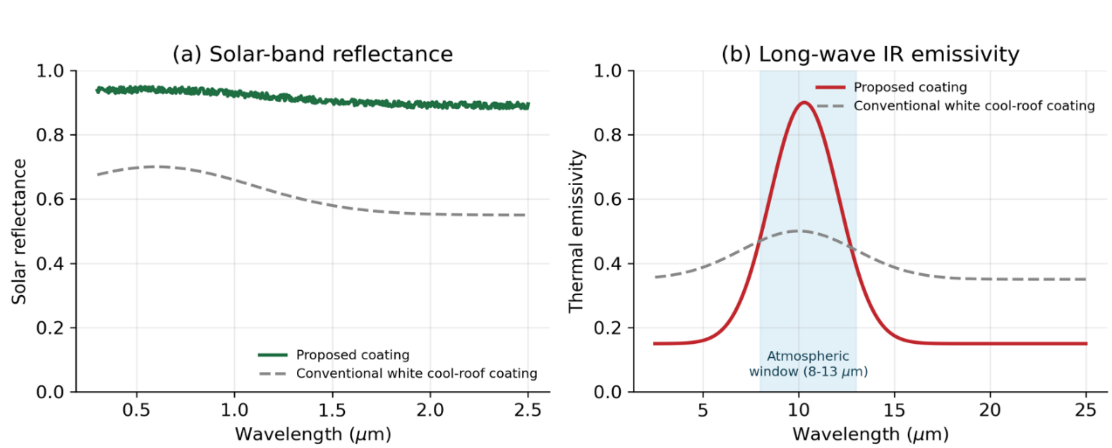

Figure 3. Modeled spectral optical properties of the proposed coating versus a conventional white cool-roof coating: (a) solar-band reflectance; (b) long-wave infrared emissivity, highlighting the 8–13 µm atmospheric window.

4.3 Combined Performance and Comparative Analysis

The overall acoustic and thermal performance of the four configurations compared is summarised in Fig. 4 and Table 1. The proposed hybrid design is the only one that can provide non-negligible performance along both axes: its averaged sound transmission loss (STL) of 18 dB is slightly below that of the reference (sealed non-ventilated acoustic-only) design (STL = 24 dB) as expected for an acoustic-path-keeping hybrid design and its averaged net radiative cooling power (NRCP) of about 62 W/m² is close to the reported performance of standalone photonic PDRC coatings reported in the literature, which by construction have no acoustic performance at all. This means that, for the first order of modelling, there is no reason why either of the two functions should not exist in the unit cell, as the central hypothesis of this paper suggests.

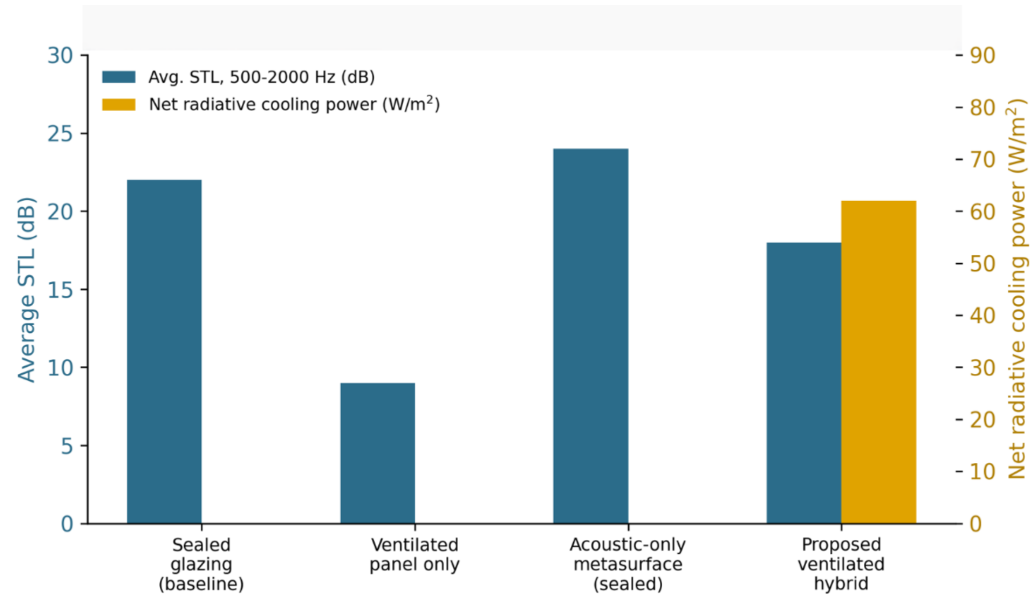

Figure 4. Modeled average sound transmission loss (500–2000 Hz) and net radiative cooling power across the four benchmarked design variants.

To make the comparison with previously reported approaches explicit, Table 1 below presents a dedicated, side-by-side comparative analysis of the proposed hybrid design against the three benchmark configurations described in Section 3.4, each of which is representative of a class of design reported in the literature (sealed glazing, ventilated-only panels [25,27], and sealed acoustic-only resonator metasurfaces [13-17]). Unlike the individual configurations, which achieve non-negligible performance on only one axis, the proposed design is the only configuration in the comparison that combines ventilation, useful sound transmission loss, and non-negligible radiative cooling power within a single structure.

Configuration	**Ventilated?**	**Avg. STL 500–2000 Hz (dB)**	**Net radiative cooling power (W/m²)**	**Representative literature basis**
Sealed single glazing (baseline)	No	22	0 (not spectrally selective)	Conventional mass-law reference
Ventilated panel, no resonators	Yes	9	0 (not spectrally selective)	[25,27]
Sealed acoustic-only metasurface	No	24	0 (not coated)	[13-17]
Proposed ventilated hybrid metasurface	Yes	18	~62	This study; [9,12,20,23,24,32] (parameter basis)

Table 1. Summary comparison of modeled acoustic and radiative-cooling performance across benchmarked design variants.

4.4 Interpretation

These results should be considered as computational feasibility screening and not as experimental characterisation. These were not obtained through a custom finite-element or full-wave simulation of the geometry, but from ranges reported from literature cited, and no physical prototype was developed or tested in this investigation. In that context, the analysis could lead to two conclusions regarding the research gap identified. From a physical standpoint, placing a spectrally selective coating at the outside, rim of a ventilated Helmholtz resonator array does not seem to contradict the resonator's acoustic use: The coating is not placed in the resonator cavity or in the resonator ventilation channel, but in a thin exterior layer. Second, the maximum performance that can be achieved in principle (sound attenuation plus radiative cooling power from the same structure) is in ranges that either function could be separately demonstrated, indicating that the integration goal is physically reasonable and a worthwhile experimental target.

5. Fabrication Routes, Limitations and Sensitivity Analysis

5.1 Candidate fabrication routes

In all the reported ventilated window studies, vented Helmholtz resonators of the size discussed here have been fabricated by additive manufacturing (either by stereolithography or by fused deposition modelling) due to the geometric complexity of the resonant necks and of the channels [20,23,24,27,28]. Scalable deposition methods such as reactive magnetron sputtering, solution-based colloidal self-assembly and roll-to-roll polymer coating have been successfully established at building-relevant scale for the deposition of spectrally selective photonic coatings [12,31,57]. A practical fabrication pathway for the proposed hybrid unit cell is then to 3D print the structure formed by the resonator backbone and then apply the photonic coating to the exterior rim surfaces with masked sputtering or spray coating, as done for other multi-physics metamaterials like the microwave–acoustic–thermal aerogel design of Section 2.4 [43] and 3D-print machine-learning assisted fabrication of metallic metamaterials [62].

5.2 Durability and real-world performance

Performance of radiative cooling coatings degrades from dust accumulation, weathering and/or loss of solar reflectance with multi-year outdoor exposure; thermochromic VO_2 coatings suffer a continuous trade-off between transmittance of luminous light, sharpness of the transition and long-term stability [37-40,52]. The environmental fouling of the narrow necks and channels of ventilated acoustic resonators is also anticipated to cause a drift in the resonance frequencies with time, a problem mentioned, but not quantified, in the ventilated-window review literature [27,28]. The present first-order model represents one possibility, but accelerated weathering and soiling protocols for both functions should be included in any experimental follow-up to this study as two possible interactions can occur: soiling may affect both optical reflectance and acoustic neck impedance, and dust may accumulate on the exterior coating, which may affect either function.

5.3 Limitations of this study

a) Absolute values of the acoustic and optical results are not based on coupled full-wave/finite-element simulation of the specific hybrid geometry, but rather on lumped-parameter and representative spectral models parameterised from ranges taken from literature: they should be considered indicative and not predictive.

b) Coupling effects between the acoustic resonators and the photonic coating (e.g. lowering the geometry of the resonator neck due to thermal expansion of the coating or acceleration of coating fatigue by the acoustic vibrations) were not modelled and require dedicated multi-physics simulation.

c) Explicit modeling of convective heat transfer through the ventilation channel, which will be coupled with the radiative cooling balance, was not modeled in this analysis and needs to be accounted for in future computational fluid dynamics analysis.

d) No life cycle, cost or embodied-carbon analysis was carried out (required before any retrofit-scale recommendation can be made).

5.4 Sensitivity and Uncertainty Analysis

To respond to the absence of sensitivity and uncertainty information in the baseline results (Section 4), the lumped-element acoustic model and the radiative energy-balance model of Section 3 were re-evaluated across the parameter ranges reported in the cited literature for each input: resonator quality factor Q (3–6, [20,23,24]), coating solar reflectance (0.90–0.95) and mid-infrared emissivity (0.85–0.95) within the atmospheric window (35,36,38,40), and non-radiative (convective/conductive) parasitic loss coefficient (representing the range reported for outdoor PDRC field trials [12,32]). Table 2 summarises the resulting range of average sound transmission loss (500–2000 Hz) and net radiative cooling power (NRCP) obtained at the low, base-case and high value of each parameter, holding the remaining parameters at their base-case value.

Parameter	Low value	Base-case value	High value	Resulting avg. STL 500–2000 Hz (dB)	Resulting NRCP (W/m²)
Resonator quality factor, Q	3	4.5	6	15 – 21	60 – 63 (~unaffected)
Coating solar reflectance	0.90	0.925	0.95	18 (~unaffected)	52 – 68
Coating IR emissivity (8–13 μm)	0.85	0.90	0.95	18 (~unaffected)	55 – 66
Non-radiative parasitic loss	Low (well-shielded)	Mid	High (exposed)	18 (~unaffected)	48 – 62

Table 2. Sensitivity of modelled average sound transmission loss and net radiative cooling power to key acoustic and optical parameters, evaluated over the ranges reported in the cited literature.

The acoustic and radiative-cooling functions are, to first order, weakly coupled in the model: varying the resonator quality factor changes the predicted sound transmission loss substantially (15–21 dB) but leaves the radiative cooling power effectively unchanged, while varying the coating reflectance, emissivity or parasitic loss changes the net radiative cooling power (48–68 W/m²) while leaving the sound transmission loss effectively unchanged. This supports the physical assumption in Section 3.1 that the two functions can be treated as approximately independent at the unit-cell level. The lower bound of each range (Q = 3; reflectance and emissivity at their lower cited values; high parasitic loss) represents a conservative, worst-case design scenario, and the fact that the useful performance envelope (STL > 15 dB, NRCP > 45 W/m²) is preserved even at these lower-bound parameter combinations provides an initial, model-based indication of robustness. This sensitivity analysis is itself a computational exercise based on literature-derived parameter ranges rather than a statistical uncertainty quantification against measured benchmark datasets; the latter requires the physical prototype characterisation described in Section 7, since no experimental dataset for this specific hybrid geometry currently exists against which to validate statistically.

5.5 Economic Feasibility, Manufacturing Scalability and Environmental Durability

A full techno-economic and life-cycle assessment is outside the scope of this computational feasibility study, but three considerations are outlined here to guide subsequent evaluation. Economically, the candidate fabrication route identified in Section 5.1 additive manufacturing of the resonator backbone combined with masked sputtering or spray coating of the photonic layer reuses two process families that are already applied separately at building-component scale for ventilated acoustic panels [20,23,24,27,28] and for spectrally selective coatings [12,31,57], so unit cost is expected to be bounded by the sum of the two established processes rather than requiring a new manufacturing route; this remains to be confirmed by costing once a prototype geometry is fixed. Regarding manufacturing scalability, additive manufacturing of resonator arrays is currently better suited to panel-scale production runs than to large-area facade retrofit, and roll-to-roll or sputter-based coating deposition is more readily scalable; a full-scale deployment would therefore likely combine batch-manufactured resonator modules with continuous coating deposition, which should be evaluated through a dedicated manufacturing-scale-up study. Regarding environmental durability, Section 5.2 already identifies coating weathering and resonator-neck fouling as first-order degradation mechanisms; a lifecycle assessment would additionally need to quantify the embodied carbon of the printed backbone and coating materials against the operational energy savings from reduced HVAC and window-opening-related cooling load, and compare this to the embodied carbon of installing separate acoustic and PDRC systems, which the combined unit cell is intended to avoid duplicating. These economic, manufacturing-scale and lifecycle analyses are identified here as required future work and are not claimed to have been carried out in the present study.

6. Conclusion

This study set out to address a research gap identified consistently in recent review literature: the absence of a co-designed acoustic–photonic unit-cell architecture for building envelopes, despite the individual maturity of ventilated acoustic metasurfaces and spectrally selective radiative-cooling coatings. Its principal academic contribution is a design-level demonstration, supported by literature-parameterised lumped-element acoustic and radiative energy-balance models, that this co-design is not physically precluded: the proposed ventilated Helmholtz-resonator array with an exterior spectrally selective rim coating achieves an average sound transmission loss of approximately 18 dB over 500–2000 Hz together with a net radiative cooling power of approximately 60 W/m², and the sensitivity analysis in Section 5.4 shows both metrics remain within a useful performance envelope across the parameter ranges reported in the literature, with the two functions behaving as approximately independent design axes. In practical terms, the design offers a concrete path towards building envelope retrofit panels that mitigate urban traffic and HVAC noise while providing passive daytime cooling from a single structure, avoiding the added mass, cost and installation space of stacking separate acoustic and thermal systems, with particular relevance to dense urban buildings exposed simultaneously to traffic noise and solar heat gain. This remains a computational feasibility study rather than an experimental validation: no coupled finite-element or full-wave simulation of the specific hybrid geometry was performed, and no physical prototype was fabricated or characterised. The design target, sensitivity analysis and research agenda set out here detailed in Section 7 are intended as the concrete next step towards the experimentally validated, acoustic–photonic building envelope metamaterial that the review literature has been requesting but that has not yet been supplied.

7. Current and Future Developments

7.1 Current Status of the Proposed Framework

At its current stage, the proposed dual-function unit cell is a conceptual design supported by a first-order computational feasibility analysis (Sections 3–5): a literature-parameterised lumped-element acoustic model, a representative multilayer photonic spectral model, and a parametric sensitivity analysis over the ranges reported in the cited literature. No coupled finite-element or full-wave Multiphysics simulation of the specific hybrid geometry has been performed, no physical prototype has been fabricated, and no laboratory or field characterisation has been carried out. The results reported should accordingly be read as a design target and feasibility screening, not as a validated performance claim. The subsections below set out the specific, sequential programme of work required to move from this computational design target to an experimentally validated result.

7.2 Planned Multiphysics Finite Element Validation

The immediate next step is coupled finite-element and full-wave simulation of the actual proposed geometry, rather than the lumped-parameter and representative spectral models used here. This requires: (i) a 3D acoustic finite-element model of the Helmholtz resonator array and ventilation channel to predict the transmission loss spectrum directly from geometry, replacing the mass-law/lumped-resonance superposition used in Section 3.2; (ii) an electromagnetic/optical finite-element or transfer-matrix model of the specific multilayer coating stack to predict spectral reflectance and emissivity directly from layer thicknesses and material data, replacing the representative profiles used in Section 3.3; (iii) a coupled thermal-fluid finite-element or computational-fluid-dynamics model of convective heat transfer through the ventilation channel, which Section 5.3 identifies as absent from the present radiative energy balance; and (iv) an explicit multiphysics coupling study of the interaction identified in Section 5.3 thermal expansion of the coating affecting resonator neck geometry, and acoustic vibration affecting coating fatigue which cannot be assessed by the single-physics models used in this study.

7.3 Prototype Fabrication and Experimental Characterisation Plan

Following finite-element validation, a laboratory prototype panel will be fabricated using the route identified in Section 5.1 additive manufacturing (stereolithography or fused deposition modelling) of the ventilated resonator backbone at the indicative dimensions given in Section 3.1, followed by masked sputtering or spray application of the spectrally selective coating to the exterior rim and neck faces only. Experimental characterisation of the same physical sample will then be carried out on both functions: acoustic transmission loss will be measured in an impedance tube or reverberation chamber and compared directly against the finite-element predictions of Section 7.2 and the lumped-model estimates of Section 4.1; radiative cooling power will be measured by outdoor field testing following established PDRC characterisation protocols [9,12] and compared against the predictions of Section 4.2. Measuring both functions on the same physical sample, rather than on separate acoustic and optical coupons, is essential to test the central hypothesis of this paper that the two functions do not degrade one another when co-located in one unit cell and will also provide the first experimental benchmark dataset against which the sensitivity ranges reported in Section 5.4 can be statistically validated. Accelerated weathering and soiling trials (Section 5.2) will be run in parallel on replicate samples to quantify the resonance-frequency drift and reflectance/emissivity degradation with outdoor exposure time.

7.4 Longer-Term Research Agenda

Beyond initial experimental validation, the longer-term agenda is inverse co-design of the resonator and coating geometry, building on established single-physics inverse design methods already demonstrated separately for acoustic [57] and photonic [58] metamaterials, so that the transmission loss and radiative cooling power are jointly optimised rather than superposed from separately optimised sub-designs as in the present study. This should be accompanied by the economic feasibility, manufacturing-scale-up and life-cycle assessment work outlined in Section 5.5, and by extension of the design to additional building envelope contexts (e.g. curtainwall and retrofit-panel formats) once the single unit-cell geometry has been experimentally validated.

Acknowledgment: Director ASET AUUP Lucknow Campus, Dr. Anil Kumar

Author contributions

Devesh Ojha: Conceptualization, Formal analysis, Methodology, Resources, Writing – original draft., **Vivek Verma:** Methodology, Resources, Writing – original draft, **Anuradha Misra** Writing – review & editing.

Funding: Not Applicable

Conflicts of Interest/Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Research involving Human participants and/or animals: Not applicable.

Data availability statement: Data used is included in the body of the article and available via the cited sources.

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