



Transparent coupled membrane metamaterials with simultaneous microwave absorption and sound reduction

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Abstract: Metamaterials offer a novel strategy to control wave propagation in different physical fields ranging from acoustic, electromagnetic, and optical waves to static electric and thermal fields. However, fundamental and practical challenges still need to be overcome for multi-physical manipulation, especially for independent control of acoustic and electromagnetic waves simultaneously. In this paper, we propose and experimentally demonstrate a transparent bifunctional metamaterial in which acoustic and electromagnetic waves could be engineered jointly and individually. Specifically, a transparent composite coupled membrane metamaterial is introduced with indium tin oxide (ITO) patterns coated on the top and bottom membranes, giving rise to simultaneous electromagnetic wave dissipation and sound reduction. Our results could help broaden the current research scope for multiple disciplines and pave the way for the development of multi-functional devices in new applications.

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1. Introduction

In the past decade, significant progress has been achieved in the development of artificial metamaterials with customizable medium parameters and versatile properties, allowing unprecedented control over wave propagation at deep sub-wavelength scale and benefiting our daily life with a wide range of applications. The metamaterial concept was initially put forward in the microwave region [1–3], and then extended to the realms of acoustics [4], mechanics [5], thermology [6] and electrostatics [7] by analogy and thus provide a powerful tool to reshape wave responses in a controlled manner. Although great strides have been made in the theoretical and experimental investigations of metamaterials within single physical field, the attempts of multifunctional manipulation in various physical domains are still largely limited by the current technology [8–14].

Recent advances in multiple physical fields have spurred great interests in addressing the challenges of multiphysical regulation [8–15]. For instance, it has been demonstrated that independent cloaking of static electric current and thermal flow by metamaterials can be achieved, where the basic element is a mixture of heat thermal and electric conductive materials [9,10]. However, the overall design requires anisotropic materials to manipulate the propagation and scattering features of both physical fields, which in turn increase the difficulty and complexity of implementation and far from the real application.

Here we report on a new scheme to construct a transparent bifunctional metamaterial with independent sound and electromagnetic (EM) responses. As an alternative to the

transformation multiphysics approach, we adopt a simple yet efficient approach to generate the desired functionalities in two physical domains by employing a coupled membrane structure. It is well known that such membrane-type metamaterial shows remarkable properties including light weight, thin profile and simple geometry. By controlling the membrane shape, size or the attached mass weight, it is possible to tailor the effective density / bulk modulus of this material at will [16–18], thereby benefiting a number of applications such as sound reduction [19–22], super-lens [23,24], extraordinary transmission [25–27], and perfect absorption [28]. In spite of the extraordinary ability of sound controlling, the proposed structure lacks essential responses to EM wave, since most membrane materials are transparent to that. To circumvent this limitation, two ultrathin ITO films are attached to the top and bottom membranes respectively as additional layers to interact with the illuminated energy [29], serving as a screen to adjust the EM transmittance without influencing the acoustic performance. In addition, such materials also possess large light transmittance, making it a good candidate for the skylights or floor glasses for modern architectures located in the environments with large noises and severe EM pollution (Fig. 1(a)). The mechanism of the multiphysics manipulation as well as the measurement approaches for experimental verification has been discussed in detail. The proposed structure provides a bridge between EM metamaterials and acoustic metamaterials, and could inspire the development of next-generation complex field systems in the future.

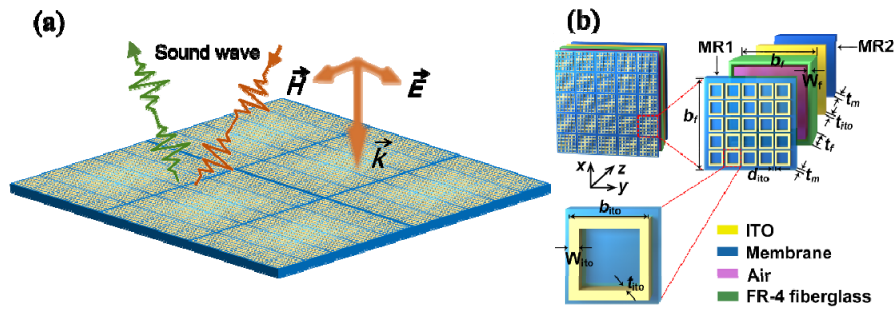


Fig. 1. (a) Illustration of the CMS metamaterial for simultaneous microwave absorption and sound reduction. (b) Schematic of the CMS metamaterials coated with ITO films and zoomed view of the meta-atom.

2. Theory and design

The key of our work is to construct a structure with independent responses to acoustic and EM waves simultaneously. To achieve this goal, we introduce a composite element by sandwiching a thin air gap between two elastic membranes as shown in Fig. 1(b). The top (MR1) and bottom (MR2) membranes, illustrated in the right inset of Fig. 1(b), are connected by a square rigid supporting frame array with the periodicity $b_f = 50\text{mm}$, side thickness $w_f = 1.5\text{mm}$ and side height $t_f = 6.5\text{mm}$, forming a periodic coupled-membrane structure (CMS) capable of blocking sound transmission over a wide bandwidth [30,31]. The frame is made of FR-4 fiberglass whose mass density, Young's modulus, and Poisson ratio are 1990 kg/m^3 , 27 GPa , and 0.33 , respectively. Both the acoustic and EM waves are assumed to be normally incident along z -direction. As seen from the zoomed inset of Fig. 1(b) right, two transparent PET (Polyethylene terephthalate) membranes with the thickness $t_m = 0.175\text{mm}$, mass density $\rho_l = 1391\text{kg/m}^3$, Young's modulus $E_l = 5.8\text{GPa}$ and Poisson's ratio $\sigma_l = 0.39$ are used to comprise the CMS. The air column in-between the CMS has the dimension of $47\text{mm} \times 47\text{mm} \times 6.5\text{mm}$. The speed of sound in air is $c_0 = 343\text{m/s}$, and the mass density is $\rho_0 = 1.29\text{kg/m}^3$. The dielectric constants for PET and FR-4 are $3.0(1 + i0.06)$ and $4.3(1 + i0.025)$ respectively. The edges of the membranes are described by fixed boundaries.

Despite the excellent sound insulation characteristics and large light transmittance, the current structure, however, lacks essential response to microwave illumination and thus

remains a significant challenge to manipulate EM radiation in a controlled manner. An attempt to address this issue involves the integration of traditional sub-wavelength EM meta-atoms within the CMS, but the metallic or dielectric elements will inevitably influence the sound transmission property. Moreover, the CMS suffers from the sharp decline of the total optical transparency, which is especially critical for applications such as soundproof windows. It would be nice if we can pattern periodic arrays of the meta-atoms on both membranes for independent controls of sound and EM waves at the same time. A promising approach toward this goal is to coat the PET membranes with an ultrathin transparent indium tin oxide (ITO) film, on which the sub-wavelength patterns could be easily obtained through the standard laser etching technology. As a transparent conductive oxide, ITO is widely utilized as the electrodes [32] to reduce the resistance when light passes through, and also a candidate for plasmonic nanoparticles [33] with low optical absorptive loss. In addition, it has been recently explored in the design of optically transparent metamaterial absorbers that it can efficiently dissipate the incoming EM energy within a wide frequency range while keeping excellent solar transmission performance, and in turn provides extra freedom in the implementation of our multifunctional device [34]. We fabricate periodic arrays of ITO square rings on the surface of MR1, and an ITO ground layer on the surface of the MR2, forming a classical microwave ring resonator with air substrate that acts as an excellent EM absorber. The incorporated ITO meta-atoms on the CMS have nearly negligible effect on the overall sound behaviors, except for a slight decrease of the light transmittance due to the moderate resistance of ITO layer, making it possible for the composite structure to respond to sound and EM waves independently. Akin to different operating wavelength for acoustic and EM waves, there is a distinction between the lattice constant of the CMS and ring element in our design. More specifically, each CMS element consists of a sub-array of 5×5 ring resonators with the geometric dimensions $b_{ito} = 8.5\text{mm}$ and $w_{ito} = 1.5\text{mm}$ as shown in Fig. 1(b). The top and bottom ITO layers have the same thickness $t_{ito} = 200\text{ nm}$, but they have the different sheet resistances of 115Ω and 5Ω respectively. In our design, the bottom ITO layer acts as the ground for the whole microwave absorber to prevent wave penetration and enhance absorption of EM waves from multiple reflections between the two layers, demanding a small sheet resistance as a result.

We first evaluate the low frequency sound insulation predicted through finite-element analysis based on the commercial solver package (COMSOL Multiphysics). Figure 2(a) illustrates the sound transmission loss (STL) spectra of the proposed element by calculating the ratio of the incident power to the transmitted power as $STL = 20\log(|p_{in}|/|p_{tr}|)$, where p_{in} and p_{tr} are the incident and the transmitted sound pressure respectively. Due to the multi-reflections of sound between MR1 and MR2, large transmission loss can be observed with STL greater than 10 dB from 400 Hz to 900 Hz within the incident angular range from 0° to 45° (Fig. 2(a)), along with two STL peaks (near 735 Hz and 800 Hz) and three STL valleys (near 245 Hz, 725 Hz, and 910 Hz) as shown in Fig. 2(a). The sound insulation performance of the proposed structure is also monitored from 1 KHz to 10 KHz in Fig. 2(c), in which excellent blocking ability is also demonstrated towards high frequency noises, showing good potential for future applications.

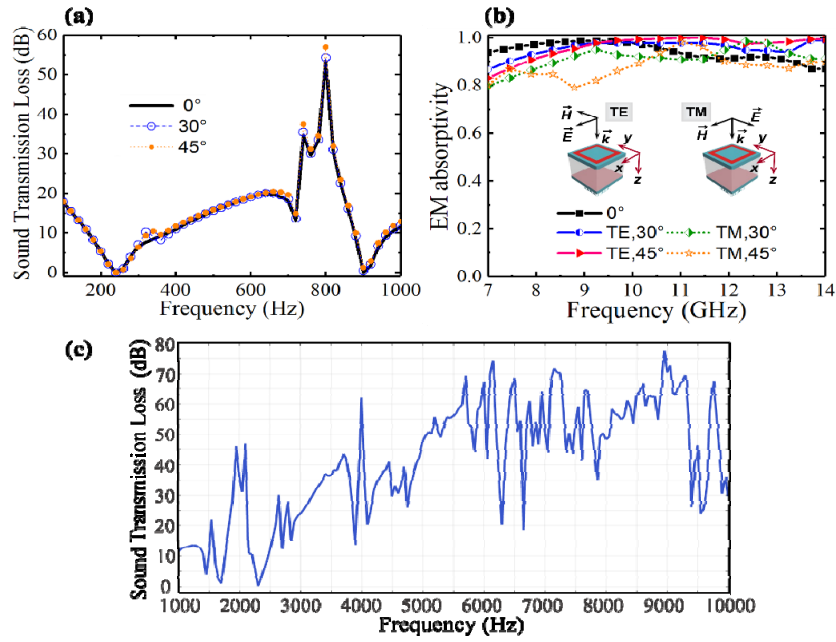


Fig. 2. Performances of the pre-designed CMS metamaterial. (a) Sound transmission loss spectra below 1 kHz. (b) EM wave absorptivity for TE/TM polarized waves at the incident angles from 0° to 45°, respectively. (c) Sound transmission loss spectra from 1 KHz to 10 KHz.

To provide an insight into the physical process responsible for the resonances, we analyze the vibration modes of the element at five characteristic frequencies as depicted in Figs. 3(a)-3(j), where the visualization of vibration profiles and the out-of-plane displacements of the two membranes along z -direction are presented under the excitation of plane sound wave [30]. For the first mode at 245 Hz (Figs. 3(a) and 3(d)), a STL valley emerges with the two membranes vibrating in phase, leading to a dipolar response to the incident wave. The air velocity, as denoted by the white arrows remains unchanged when transmitting through the top and bottom membranes, and nearly no backward air flow can be found as demonstrated in Fig. 3(d). However, for the second mode at 725 Hz (Figs. 3(b) and 3(e)), a monopolar resonance is clearly observed from the out-of-phase vibration of the two membranes, in which the air flow is concentrated in the middle region and forced to move along the transverse direction, with opposite air velocity at both sides of the CMS elements. The third mode corresponds to the STL valley at 910 Hz (Figs. 3(c) and 3(f)). Similar to the first mode, this resonance arises from the in-phase vibration of the two membranes, which can also be attributed to the dipolar response. The difference between the two modes lies in the profile of the membrane displacement in the z direction, which behaves as a half wave and 3/2 wave resonators along the radial direction. Figures 3(g)-3(j) illustrate the modal features at the first and second STL peaks ($f = 735\text{Hz}$ and 800Hz), where the transmitted sound waves decay rapidly along the normal of the membranes. Intense circulation motions of air can be found with a rapid decrease near the MR1 and MR2 due to the interference of internal modes, and the air on the transmission sides are almost completely motionless, forming an efficient barrier for the incident sound.

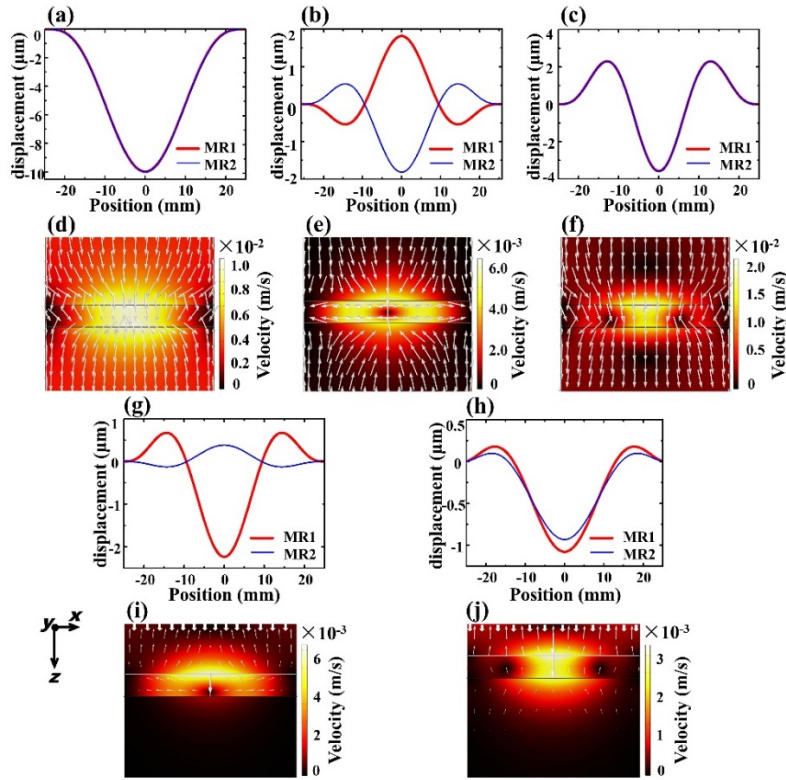


Fig. 3. Displacements of MR1 and MR2 and the air motions at eigenfrequencies $f = 245$ Hz (a) (d), 725 Hz (b)(e), and 910 Hz (c)(f) respectively. Displacements and the corresponding air motions excited by incident sound wave are also provided at $f = 735$ Hz (g)(i) and 800 Hz (h)(j) respectively.

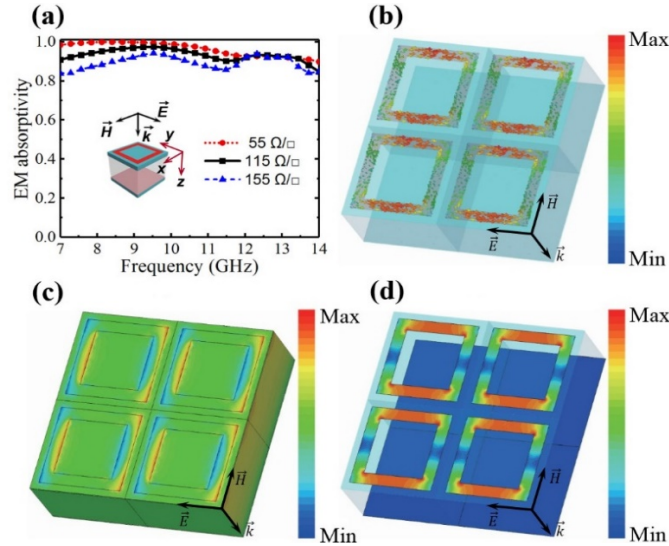


Fig. 4. EM Properties produced by the separated ITO square arrays without rigid frames. (a) Absorptivity of the meta-atom with the different sheet resistance of the top ITO layer at normal incidence of plane wave, and (b) surface currents, (c) electric field and (d) surface loss density on the top of the ITO rings at 9.5 GHz.

Next we proceed to investigate the EM responses of the proposed metamaterial. A large absorptivity greater than 80% can be obtained at the incident angle up to 45° in the frequency range of 9-14 GHz (Fig. 2(b)). To understand the background mechanism of EM absorption, the simulated absorptivity, surface currents, electric field and surface power loss density of the meta-atom are demonstrated in Figs. 4(a)-4(d) respectively under the normal incidence. In the vicinity of the absorption peak $f = 9.5$ GHz, most of the surface currents are found to be primarily confined on the surface of the square rings (Fig. 4(b)) through numerical simulations (CST Microwave Studio), which stem from the electric resonance driven by the external field. This can be further confirmed by inspecting the distribution of electric field and surface loss density within the elements as shown in Figs. 4(c) and 4(d), indicating a large electric loss due to the absence of anti-parallel current to generate the magnetic resonance in demand. We observe that most of the electric energy is dissipated through the ohmic loss of ring at the top membrane, and thus it is proper to choose a relatively large sheet resistance to promote EM absorption. However, the input impedance of the CMS element should be carefully monitored to avoid severe impedance mismatch to that of free space, since that may result in undesired increase of EM reflection from the top membrane. The present design can also permit polarization independent absorption of microwave energy thanks to the symmetry of the element geometry, which is critical for various applications in a wide variety of technologies. In addition, the increase of the sheet resistance of the top ITO layer leads to the reduction of overall absorption bandwidth as revealed in Fig. 4(a), but results in enhanced optical transparency at the same time. To seek the balance between the optical transmittance and microwave absorption, the sheet resistance of the top ITO layer ($115 \Omega/\square$) is finally determined after optimization. Moreover, the bottom ITO layer with low sheet resistance ($5 \Omega/\square$) is chosen to mimic the metallic ground, which can block most of the incident EM wave.

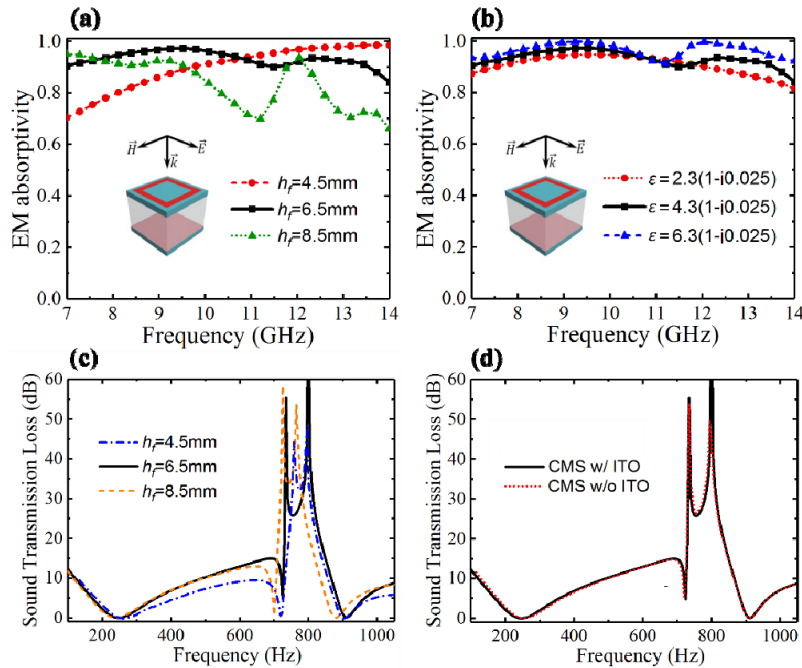


Fig. 5. (a) Dependence of the simulated EM wave absorptivity spectra on the thickness h_f , (b) dielectric constant ϵ_f of the FR-4 frame at normal incidence. Insets: Orientation of incident wave. (c) STL of the CMS with the increase of the membranes distance h_f between MR1 and MR2, and (d) STL of the double-layer membranes with/without ITO.

One important concern we need to mention is the interplay between the two mechanisms, namely how the dynamic vibration affects the absorption performance of the CMS, which is not included in the simulation. This can be understood by reviewing the membrane displacement illustrated in Fig. 3. It is clearly observed that the membranes oscillate at the scale of micrometers, which are far smaller than the EM wavelength at the working frequencies, and thus yielding negligible phase delay upon the transmitted waves [35]. In addition, the influence of the periodic rigid frames on the EM behavior has also been taken into account, since the reflection on the facet will be excited owing to the impedance mismatch between air and the frame as shown in Figs. 5(a) and 5(b). The absorptivity spectra of the CMS as the function of the frame thickness h_f is presented in Fig. 5(a). A moderate value $h_f = 6.5\text{mm}$ is selected to avoid possible fluctuations of the reflection amplitude. Moreover, the influence of the frame material permittivity is also studied in Fig. 5(b). With the increase of the frame permittivity ε , minor distinctions are observed in the absorptivity curves at high frequencies. Thus it is proper to use FR-4 (with $\varepsilon = 4.3(1 + i0.025)$) as the supporting material in our design due to its excellent mechanical properties.

The dependence of the membrane distance on the STL response is also explored in Fig. 5(c). The increasing of the distance h_f from 4.5mm to 8.5mm leads to a shift toward lower resonance frequencies, while the two STL peaks seem to approach with reduced bandwidth of sound blocking. The incremental gap size between the top and bottom membranes will elongate the resonance length along the normal direction, which in turn causes the decline of the eigenfrequencies [36]. Actually, the thickness of 6.5mm is quite thin ($\sim \lambda/132$ at 400Hz) for low frequency sound insulation according to the mass density law.

Furthermore, numerical simulations have also been made to check the STL variance of the CMS with or without the ITO films in Fig. 5(d), proving that the presence of the ITO layer is nearly irrelevant to the sound insulation behavior. Note that although the PET membrane is not so strong to resist the outside forces right now, we think the mechanical stability can be further improved by replacing it by harder membrane in future applications.

3. Experiments and discussions

To confirm the theoretical analyses and the simulation results, two separate experiments are carried out to characterize the sample with the size of $250\text{mm} \times 250\text{mm}$ (Fig. 6(a)). The STL of the sample is measured inside an impedance tube based on the transfer matrix method (Fig. 6(b)) and the EM absorption is measured by the free space method (Fig. 6(c)). To attach the periodic ITO elements on both membranes, the strong double-side adhesive tapes (3M467MP) are used for interlayer adhesion between the membrane and the frame with the total thickness $50\text{ }\mu\text{m}$. A logo of Southeast University is placed behind the sample to check its transparency, which can be clearly observed as shown in Fig. 6(a). Based on the classical transfer matrix method as described in [37], the average light transmittance of the sample reaches approximately 79% at normal incidence, confirming the high transparency of the designed structure. During the microwave measurement, a high-gain broadband lens antenna is employed to transmit and receive swept sinusoidal signals from 7GHz to 14GHz when connected to one port of the vector network analyzer (Agilent 5230C). The sample is mounted on a specifically designed holder made of polymethacrylimide (PMI), which produces negligible influence on the measurement results due to its low dielectric constant $1.05(1 + i0.001)$.

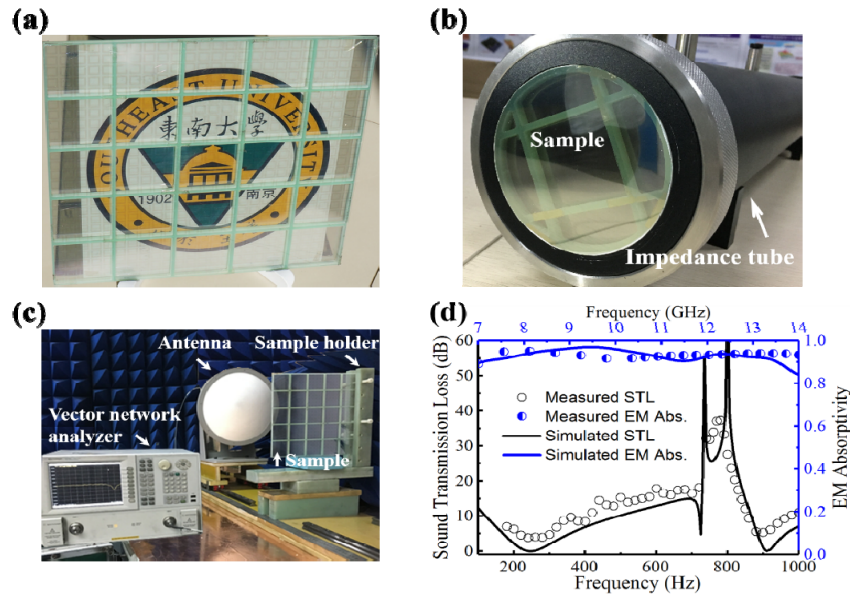


Fig. 6. (a) Photograph of the fabricated sample. (b) The impedance tube for the measurement of STL. (c) Test scenario of the absorptivity measurement via the free space method. (d) The simulated (black solid line) and measured (black hollow circles) STL, along with the simulated (blue solid line) and measured (blue hollow circles) absorptivity.

Two rounds of measurement are carried out for calibration and normalization of the reflectivity, in which both the sample and a control metallic plate of the same size are measured for comparison [34]. Although the absorptivity strictly depends both on the transmitting and reflecting features on the sample as $A = 1 - |S_{11}|^2 - |S_{21}|^2$, the transmittivity of the sample is very small compared to the reflectivity since most energy will be blocked by the ITO ground of the structure, hence, the absorptivity across the entire frequency range can be further simplified as $A = 1 - |S_{11}|^2$. The STL measurement is performed within a large impedance tube (BSWA Technology Co.). The apparatus comprises two type-SW422 impedance tubes and the sample is firmly sandwiched in between. The transfer function method is utilized to measure the STL [38]. A loudspeaker is mounted at one end of the front tube. Four microphones are situated at four predefined positions along the tubes. An open-ended tube condition and a hard close-ended tube condition are applied for the STL experiment. The frequency range is assumed to be 100 Hz to 1000 Hz. The results are averaged over ten experiments.

The experimental STL and EM absorptivity spectra are illustrated by black and blue dot curves in Fig. 6(d), respectively. The measured STL is observed to be coincident with the numerical predictions, showing a powerful sound insulation ability within the frequency range from 100Hz to 1000Hz. The discrepancy between the numerical and measured results can be possibly attributed to the lossless assumption of the two membranes, where the viscosity effect is not taken into account in the simulations. Additionally, large EM absorptivity of higher than 85% is supported at normal incidence from 7GHz to 14GHz, corresponding to the resonant loss as revealed in Fig. 4. A red shift occurs at the first resonance frequency of the absorptivity spectra, which may be caused by the deviation of the sheet resistance from ideal value for the ITO films and the fact that the double-sided adhesive tape is not included in the simulations. Overall, efficient manipulations of both sound and EM waves are achieved at the same time through experiments, consistent with the features observed in the numerical simulations.

4. Conclusions

To summarize, a coupled membrane-ITO metamaterial is designed for independent controls of sound insulation and EM absorption simultaneously. The two membranes form a cavity to block the incident sound due to the presence of resonance modes, while the ITO patterns attached to the membranes can efficiently dissipate the EM energy in a wide bandwidth due to the electric resonances induced by the normal direction illumination. Such a platform possesses the advantages of light weight, thin profile and low cost, hereby providing an important way toward solving important multiphysics problems for future applications.

Funding

National Key Research and Development Program of China (2017YFA0700201, 2017YFA0700202, 2017YFA0700203); National Natural Science Foundation of China (NSFC) (61631007, 61138001, 61371035, 11227904, 61731010, 61571117, 61501112, 61501117, 61522106, 61722106, 61701107, and 61701108); 111 Project (111-2-05); Natural Science Foundation of Jiangsu Province (BK20150020); Fundamental Research Funds for the Central Universities (KYCX17_0091); Scientific Research Foundation of Graduate School of Southeast University (YBJJ1711).

References

1. V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of permittivity and permeability," *Sov. Phys. USPEKHI* **10**, 509 (1968).
2. J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, "Extremely low frequency plasmons in metallic mesostructures," *Phys. Rev. Lett.* **76**(25), 4773–4776 (1996).
3. D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.* **84**(18), 4184–4187 (2000).
4. Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan, and P. Sheng, "Locally resonant sonic materials," *Science* **289**(5485), 1734–1736 (2000).
5. R. Zhu, X. N. Liu, G. K. Hu, C. T. Sun, and G. L. Huang, "Negative refraction of elastic waves at the deep-subwavelength scale in a single-phase metamaterial," *Nat. Commun.* **5**(1), 5510 (2014).
6. S. Narayana and Y. Sato, "Heat flux manipulation with engineered thermal materials," *Phys. Rev. Lett.* **108**(21), 214303 (2012).
7. Y. Zeng, Q. Wu, and D. H. Werner, "Electrostatic theory for designing lossless negative permittivity metamaterials," *Opt. Lett.* **35**(9), 1431–1433 (2010).
8. T. Han, X. Bai, J. T. Thong, B. Li, and C. W. Qiu, "Full control and manipulation of heat signatures: cloaking, camouflage and thermal metamaterials," *Adv. Mater.* **26**(11), 1731–1734 (2014).
9. M. Moccia, G. Castaldi, S. Savo, Y. Sato, and V. Galdi, "Independent manipulation of heat and electrical current via bifunctional metamaterials," *Phys. Rev. X* **4**(2), 021025 (2014).
10. Y. Ma, Y. Liu, M. Raza, Y. Wang, and S. He, "Experimental demonstration of a multiphysics cloak: manipulating heat flux and electric current simultaneously," *Phys. Rev. Lett.* **113**(20), 205501 (2014).
11. J. Xu, X. Jiang, N. Fang, E. Georget, R. Abdeddaim, J. M. Geffrin, M. Farhat, P. Sabouroux, S. Enoch, and S. Guenneau, "Molding acoustic, electromagnetic and water waves with a single cloak," *Sci. Rep.* **5**(1), 10678 (2015).
12. Y. Yang, H. Wang, F. Yu, Z. Xu, and H. Chen, "A metasurface carpet cloak for electromagnetic, acoustic and water waves," *Sci. Rep.* **6**(1), 20219 (2016).
13. C. Lan, K. Bi, Z. Gao, B. Li, and J. Zhou, "Achieving bifunctional cloak via combination of passive and active schemes," *Appl. Phys. Lett.* **109**(20), 201903 (2016).
14. C. Lan, K. Bi, X. Fu, B. Li, and J. Zhou, "Bifunctional metamaterials with simultaneous and independent manipulation of thermal and electric fields," *Opt. Express* **24**(20), 23072–23080 (2016).
15. S. Zhong, L. Wu, T. Liu, J. Huang, W. Jiang, and Y. Ma, "Transparent transmission-selective radar-infrared bi-stealth structure," *Opt. Express* **26**(13), 16466–16476 (2018).
16. Z. Yang, J. Mei, M. Yang, N. H. Chan, and P. Sheng, "Membrane-type acoustic metamaterial with negative dynamic mass," *Phys. Rev. Lett.* **101**(20), 204301 (2008).
17. A. Allam, A. Elsabbagh, and W. Akl, "Modeling and design of two-dimensional membrane-type active acoustic metamaterials with tunable anisotropic density," *J. Acoust. Soc. Am.* **140**(5), 3607–3618 (2016).
18. T. Y. Huang, C. Shen, and Y. Jing, "On the evaluation of effective density for plate- and membrane-type acoustic metamaterials without mass attached," *J. Acoust. Soc. Am.* **140**(2), 908–916 (2016).
19. Z. Yang, H. M. Dai, N. H. Chan, G. C. Ma, and P. Sheng, "Acoustic metamaterial panels for sound attenuation in the 50–1000 Hz regime," *Appl. Phys. Lett.* **96**(4), 041906 (2010).

20. L. Fan, Z. Chen, S. Y. Zhang, J. Ding, X. J. Li, and H. Zhang, "An acoustic metamaterial composed of multi-layer membrane-coated perforated plates for low-frequency sound insulation," *Appl. Phys. Lett.* **106**(15), 151908 (2015).
21. N. Sui, X. Yan, T. Y. Huang, J. Xu, F. G. Yuan, and Y. A. Jing, "A lightweight yet sound-proof honeycomb acoustic metamaterial," *Appl. Phys. Lett.* **106**(17), 171905 (2015).
22. X. Wang, H. Zhao, X. Luo, and Z. Huang, "Membrane-constrained acoustic metamaterials for low frequency sound insulation," *Appl. Phys. Lett.* **108**(4), 041905 (2016).
23. J. J. Park, C. M. Park, K. J. B. Lee, and S. H. Lee, "Acoustic superlens using membrane-based metamaterials," *Appl. Phys. Lett.* **106**(5), 051901 (2015).
24. C. Shen, Y. Xie, N. Sui, W. Wang, S. A. Cummer, and Y. Jing, "Broadband acoustic hyperbolic metamaterial," *Phys. Rev. Lett.* **115**(25), 254301 (2015).
25. Y. Jing, J. Xu, and N. X. Fang, "Numerical study of a near-zero-index acoustic metamaterial," *Phys. Lett. A* **376**(45), 2834–2837 (2012).
26. C. Shen, J. Xu, N. X. Fang, and Y. Jing, "Anisotropic complementary acoustic metamaterial for canceling out aberrating layers," *Phys. Rev. X* **4**(4), 041033 (2014).
27. Y. Gu, Y. Cheng, J. Wang, and X. Liu, "Controlling sound transmission with density-near-zero acoustic membrane network," *J. Appl. Phys.* **118**(2), 024505 (2015).
28. J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, and P. Sheng, "Dark acoustic metamaterials as super absorbers for low-frequency sound," *Nat. Commun.* **3**(1), 756 (2012).
29. D. Hu, J. Cao, W. Li, C. Zhang, T. Wu, Q. Li, Z. Chen, Y. Wang, and J. Guan, "Optically transparent broadband microwave absorption metamaterial by standing-up closed-ring resonators," *Adv. Opt. Mater.* **5**(13), 1700109 (2017).
30. M. Yang, G. Ma, Z. Yang, and P. Sheng, "Coupled membranes with doubly negative mass density and bulk modulus," *Phys. Rev. Lett.* **110**(13), 134301 (2013).
31. J. S. Chen, Y. B. Chen, H. W. Chen, and Y. C. Yeh, "Bandwidth broadening for transmission loss of acoustic waves using coupled membrane-ring structure," *Mater. Res. Express* **3**(10), 105801 (2016).
32. N. Zhou, H. Chen, J. Li, and L. Chen, "Highly sensitive and selective voltammetric detection of mercury (II) using an ITO electrode modified with 5-methyl-2-thiouracil, graphene oxide and gold nanoparticles," *Microchimica Acta* **180**(5–6), 493–499 (2013).
33. A. Kim, Y. Won, K. Woo, C. H. Kim, and J. Moon, "Highly transparent low resistance ZnO/Ag nanowire/ZnO composite electrode for thin film solar cells," *ACS Nano* **7**(2), 1081–1091 (2013).
34. C. Zhang, Q. Cheng, J. Yang, J. Zhao, and T. J. Cui, "Broadband metamaterial for optical transparency and microwave absorption," *Appl. Phys. Lett.* **110**(14), 143511 (2017).
35. C. J. Naify, C. M. Chang, G. McKnight, and S. Nutt, "Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials," *J. Appl. Phys.* **108**(11), 114905 (2010).
36. S. H. Lee, C. M. Park, Y. M. Seo, Z. G. Wang, and C. K. Kim, "Acoustic metamaterial with negative density," *Phys. Lett. A* **373**(48), 4464–4469 (2009).
37. P. Yeh, *Optical Waves in Layered Media* (Wiley, 1988).
38. K. M. Ho, Z. Yang, X. X. Zhang, and P. Sheng, "Measurements of sound transmission through panels of locally resonant materials between impedance tubes," *Appl. Acoust.* **66**(7), 751–765 (2005).