

# Multi-mechanism assisted ultrathin labyrinthine metastructure for ultrabroadband sound insulation

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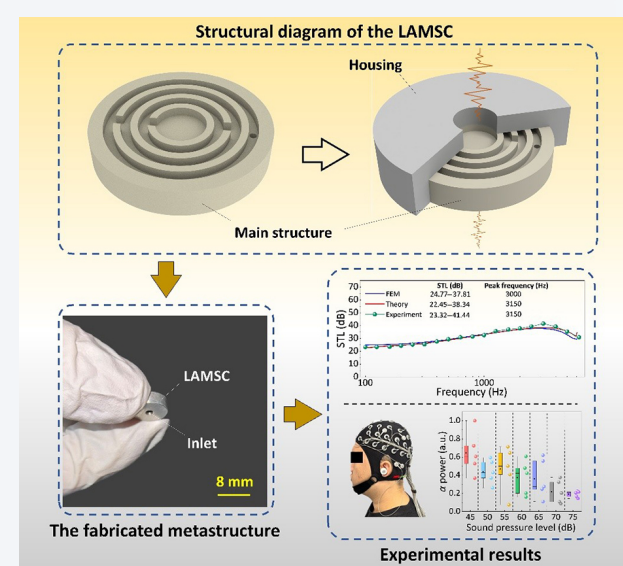
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**ABSTRACT:** Acoustic metastructures, with designable operating frequency bands and sub-wavelength artificial units, have been extensively studied in recent years for noise attenuation. However, existing metastructures commonly sacrifice structural compactness to increase operating bandwidth, thereby limiting their applications in wearable scenarios. To overcome this challenge, we propose an ultrathin labyrinthine acoustic metastructure featuring submillimeter-scale channels (LAMSC) with overall dimensions of 9.5 mm × 2.3 mm (diameter × thickness). Acoustic tests demonstrate ultrabroadband sound insulation across 100–6000 Hz range, which includes three sub-frequency bands dominated by thermoviscous absorption, acoustic reflection, and resonant absorption mechanisms, respectively. The sound transmission loss (STL) reaches 23.32–41.44 dB over the tested frequency range, along with a flatness of 14.43 dB@100–2000 Hz representing an improvement of 3.57–55.57 dB over the previously reported sound insulation metastructures. Then, the LAMSC is integrated into earplugs for  $\alpha$  band electroencephalogram test under traffic noise, demonstrating a noise reduction of at least 20 dB. This work offers combined advantages of structural compactness and broadband sound insulation, providing the potential to be used for noise isolation in earplugs and other space-constrained applications.

**KEYWORDS:** labyrinthine acoustic metastructure, thermoviscous absorption, acoustic reflection, resonant absorption, ultrabroadband sound insulation, compact structure

## 1 Introduction

Noise pollution currently ranks as the second-largest environmental risk to human health, affecting individuals both physiologically and psychologically [1, 2]. The World Health Organization estimates that over 1.5 billion people worldwide are at risk of hearing loss due to noise exposure, where wearing sound insulation earplugs serves as a key preventive measure [3]. Considering limited space of the



ear canal and outer ear as well as the need for long-term wearing comfort, sound insulation materials inside the earplug must be compact while providing broadband attenuation. Although traditional materials, including gradient-index materials [4], porous fibers materials [5, 6], and porous foams materials [7], can provide effective insulation, the improvement of operating bandwidths typically comes at the cost of lightweight and miniaturized construction [8, 9].

Acoustic metastructures composed of subwavelength artificial units exhibit extraordinary properties that are unattainable in natural materials [10, 11], such as negative mass density [12, 13], negative modulus [14], or double negative characteristics [15]. Among sound-insulating metastructures, reflective-type [16–24] and absorptive-type [20, 25–31] are the most widely studied. Both

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types enhance low-frequency sound insulation by shifting their resonance peaks down into the low-frequency range. Achieving such a downward shift inevitably requires enlarging the structural dimensions, such as increasing Helmholtz cavity volume [26, 29, 32], adding attached mass [19, 30], or enlarging the plate/membrane radius [16]. Although these configurations enable low-frequency sound insulation, the operating bandwidth remains inherently narrow because sound attenuation is dominated by a single resonant feature. To overcome this limitation, a common approach is to integrate multiple resonators with different resonant frequencies, including coupling Helmholtz resonators of varying sizes or arranging plate units with graded masses reasonably [31, 33, 34]. However, these strategies still sacrifice structural compactness and fail to provide effective attenuation below the first resonance peak. This inherent trade-off between low-frequency broadband performance and miniaturization remains a challenge in the design of acoustic metastructures.

Building upon Helmholtz-type metastructures, the labyrinthine acoustic metastructure leverages space-coiling channels to achieve more compact designs while enhancing noise suppression through visco-thermal losses in narrow acoustic channels [35]. For example, in 2018, Ghaffarivardavagh et al. experimentally demonstrated the ability of such labyrinthine structure to modulate acoustic wave amplitudes [36]. Then in 2020, Kumar et al. developed a labyrinthine metastructure exhibiting a peak absorption coefficient of 0.99 at 852 Hz, with over 0.5 absorption coefficients across 530–1230 Hz [37]. Recently, in 2025, Yu et al., inspired by the asymmetric wall structure of cuttlebone, developed a labyrinthine acoustic metastructure with an average sound absorption coefficient of 0.80 in the bands of 490–660 and 620–810 Hz [38]. Also in that year, Cao et al. reported a fractal labyrinthine acoustic metastructure, with near-perfect absorption coefficients of 0.99, 0.95, and 0.95 at 265, 176, and 157 Hz, respectively [39]. However, these studies rely on designing one or several widely spaced Helmholtz resonance peaks within the operating frequency band, which limits their applicability for ultrabroadband sound insulation.

Hence, in this work, we present an ultrathin labyrinthine acoustic metastructure featuring submillimeter-scale channels (LAMSC). This design is capable of achieving ultrabroadband sound insulation via multiple synergistic physical mechanisms, i.e., the thermoviscous losses absorption (100–320 Hz), the acoustic reflection (320–2300 Hz), and the resonant absorption (2300–6000 Hz). Compared to existing acoustic metastructures, the proposed structure offers significant advantages in ultrathin thickness (2.3 mm), high sound transmission loss (STL) (23.32–41.44 dB@100–6000 Hz), and flat STL curve (14.43 dB@100–2000 Hz). Then, the fabricated LAMSC was integrated into earplugs for electroencephalogram (EEG) response tests under traffic noise (100–6000 Hz), gaining at least 20 dB of noise reduction.

## 2 Methods

### 2.1 Materials

Epoxy resin adhesive was obtained from Devcon (America). The LAMSC was machined by Beijing Keso Precision Machinery Co., Ltd., China. The fabricated main structure and housing were characterized using the extended depth of field (EDF) microscope (KC-X3000, KathMatic, China). The frame of the earplug was

fabricated by three-dimensional (3D) printing using polylactic acid (PLA). The soft cushion of the earplug was obtained from commercially earplugs (3M, America).

### 2.2 Acoustic measurement setup

During the acoustic experiment over the frequency range of 100–6000 Hz, two types of impedance tubes were used: one with an inner diameter of 100 mm (SW4201, BSWA TECH, China) and the other with an inner diameter of 29 mm (SW4601, BSWA TECH, China). The 100 mm tube (100–1600 Hz) and the 29 mm tube (500–6400 Hz) were both compliant with ASTM E2611 standard, ensuring the reliability of our measurements across the tested frequency range. A 3.5-inch loudspeaker from BSWA TECH (China) was mounted inside the impedance tubes to generate the acoustic signal, driven by a power amplifier (PA50, BSWA TECH, China). The acoustic signals in the incident and transmission fields of the impedance tubes were recorded using four identical microphones (MPA416, BSWA TECH, China). The outputs from the microphones were collected by a signal analyzer (MC3242A, BSWA TECH, China).

### 2.3 EEG measurement

#### 2.3.1 Experimental conditions and setup

To avoid interference from ambient noise, the experiment was conducted in a quiet room with a background noise level of 20–30 dB. During the experiment, traffic noise (100–6000 Hz) was played at seven SPLs, including 45, 50, 55, 60, 65, 70, and 75 dB. EEG signals were recorded using a NeuroHUB system (Neuracle, China) at a sampling rate of 1000 Hz. To accurately assess the impact of traffic noise on the  $\alpha$  power of EEG, the EEG signals from 29 channels were collected. It should be noted that the 29 channels consist of Fp1, Fp2, F3, F4, F7, F8, and Fz (frontal lobe); P3, P4, P7, P8, Pz, O1, O2, and Oz (occipital lobe); FC1, FC2, FC5, FC6, C3, C4, Cz, CP1, CP2, CP5, and CP6 (parietal lobe); T7 and T8 (temporal lobe); and FCz (localizing electrode).

#### 2.3.2 Experimental procedure

**Preparation stage.** A healthy male participant was introduced to the experimental procedure and fitted with the electrode cap, followed by a 30-min quiet sitting to minimize the influence of the preceding environment. Also, the participant would be required to close eyes and minimize unnecessary body movements to reduce artifacts unrelated to the sound stimuli during EEG signal acquisition.

**Experimental stage.** After the participant wore the earplugs with LAMSC, the EEG signals were acquired under traffic noise stimulation. Notably, the traffic noise at different SPLs was played randomly and each noise lasted 5 min. Furthermore, to eliminate the effects of prior exposure on the EEG signal, a 5-minute period without sound was introduced between each traffic noise. By contrast, the participant would be required to wear earplugs without LAMSC and repeat the same experimental procedure.

**Data preprocessing stage.** Considering that continuous 5-min EEG recordings may be affected by fluctuations in the participant's state, the recorded 5-min EEG data were divided into five consecutive 1-min epochs to verify the repeatability of the noise-reduction effect, which consists of the six steps as follows:

- i. Electrodes positioning;
- ii. A band-pass filter was applied to remove signals outside the

1–45 Hz frequency range, and then a notch filter was used to eliminate power line interference at 50 Hz;

iii. Independent component analysis (ICA) was utilized to remove artifacts caused by blinking, eye movements, and muscle activity;

iv. The data were re-referenced to the average of all electrodes to maximize the EEG response to the acoustic stimuli;

v. The data were segmented into 1-s epochs by baseline correction, with epochs exhibiting amplitudes exceeding  $\pm 60 \mu\text{V}$  being excluded;

vi. The valid epochs were averaged to further reduce random noise.

Note that the aforementioned preprocessing steps were performed using the EEGLAB toolbox (2025 version) on MATLAB R2022a. Meanwhile, the EEG experiment was approved by Bio and Medical Ethics Committee at Beihang University (Approval number: BM20260006).

### 3 Results and discussion

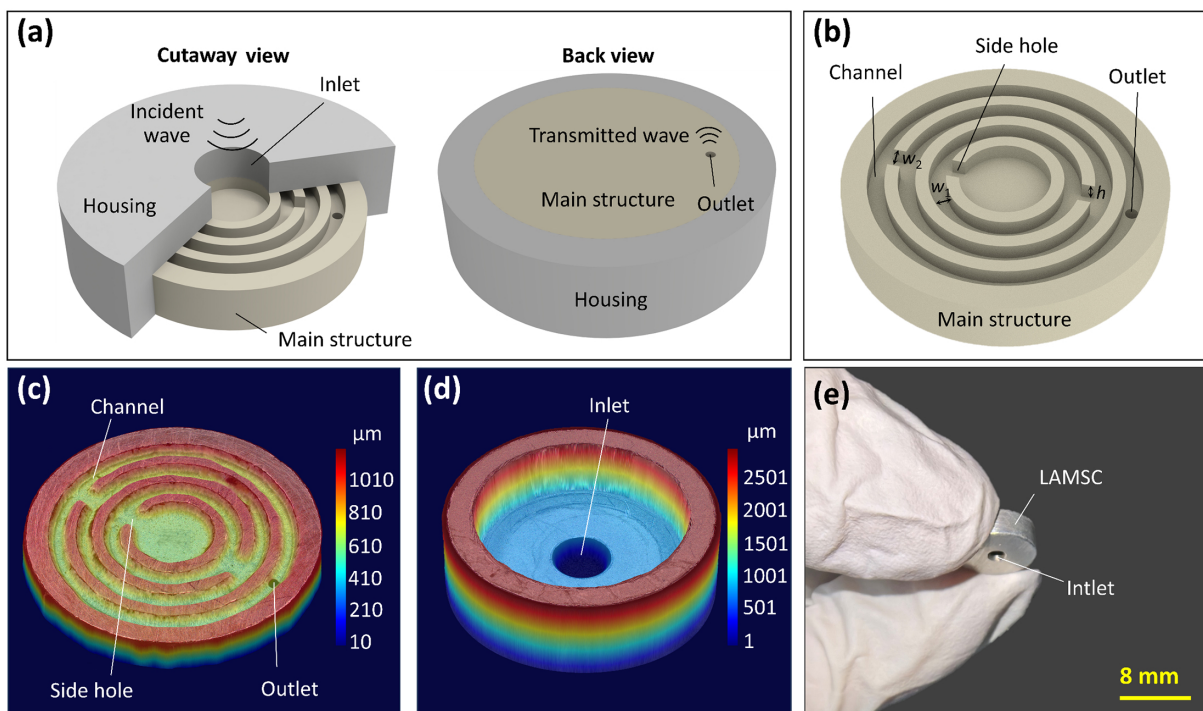
#### 3.1 Structure and mechanism of LAMSC

Unlike a micro-perforated panel-type metastructures, the proposed LAMSC consists of two main parts: a housing and a main structure (Fig. 1(a)). A circular inlet with a diameter of 2.1 mm is located on the end face of the housing. The labyrinthine channel is formed by concentric annular channels interconnected through side holes (Fig. 1(b)). Notably, the adjacent side holes are staggered by  $180^\circ$ , a design that forces the acoustic wave to traverse a semicircular path, thereby maximizing the propagation distance and thermoviscous losses. It is worth noting that this thermoviscous losses effect can also be referred to as the acoustic capillary effect [40]. The channel height is denoted as  $h$ , while the widths of the annular channels and the side holes are  $w_1$  and  $w_2$ , respectively. The incident sound wave

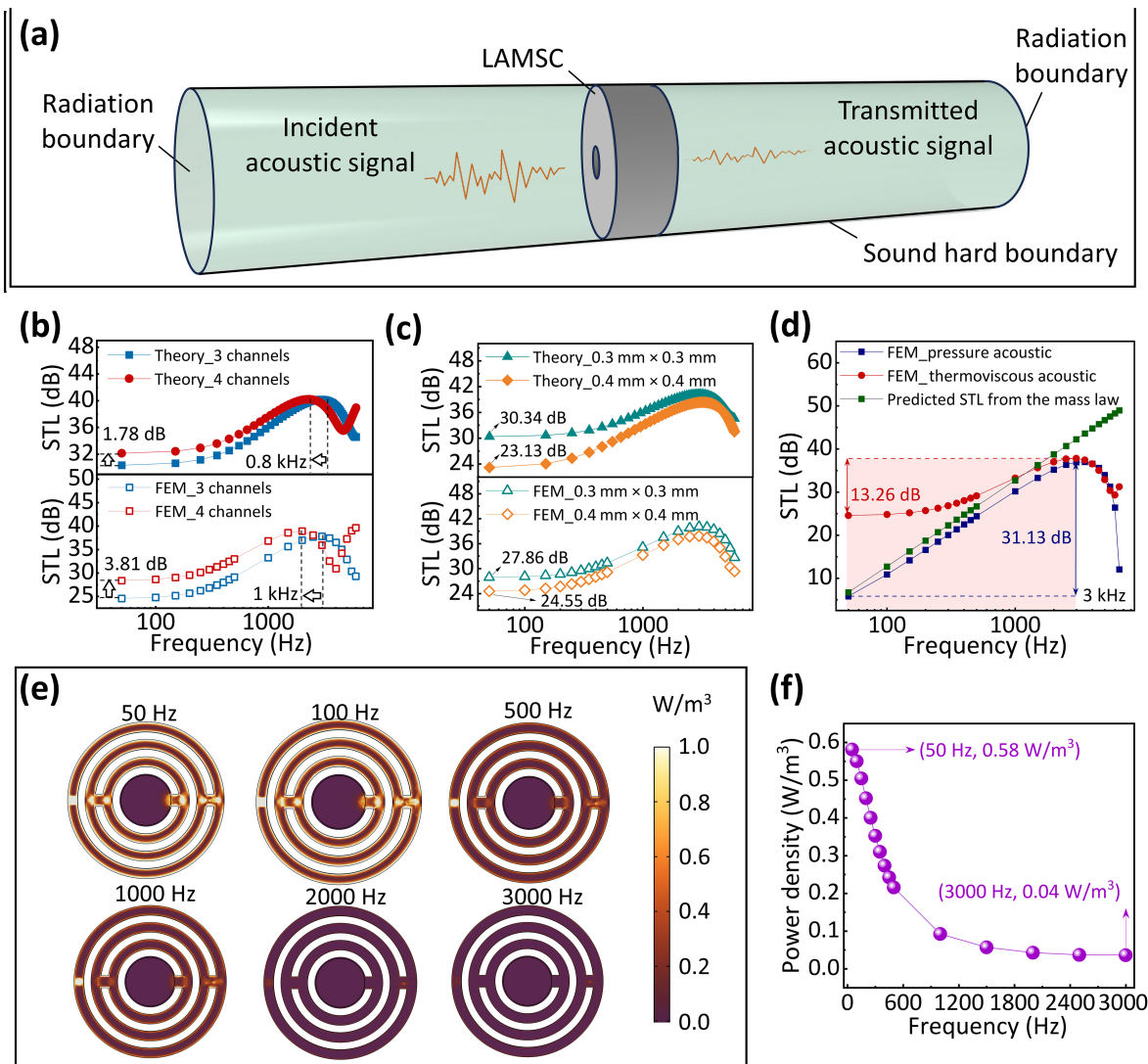
enters through the inlet, passes through the labyrinthine channel, and exits via an outlet.

The housing and main structure were fabricated from 6061 aluminum alloy by machining (Fig. S1 in the Electronic Supplementary Material (ESM)). Following fabrication, the components were assembled according to the relative positional configuration illustrated in Fig. 1(a) and bonded with epoxy resin adhesive. The fabricated main structure and housing are examined using an EDF microscope (Figs. 1(c) and 1(d)), revealing clearly defined concentric annular channels and the outlet on the main structure. In addition, photographs of the prepared main structure and housing can be found in Fig. S2 in the ESM. The photo of the fully assembled LAMSC is shown in Fig. 1(e), with an overall dimension of  $9.5 \text{ mm} \times 2.3 \text{ mm}$  (diameter ( $D$ )  $\times$  thickness ( $L$ )). In this case, the assembled LAMSC shifts the Helmholtz resonance to higher frequencies through its compact channel dimensions, while simultaneously achieving pronounced thermoviscous losses at low frequencies (more details can be found in Note S1 in the ESM).

In order to validate the sound insulation performance, the finite element model (FEM) of the LAMSC was meshed with free tetrahedron elements, with a maximum element size not exceeding  $1/8$  of the minimum wavelength of excitation frequency (Fig. 2(a) and Fig. S3 in the ESM) [27]. Given the negligible influence of sound-structure coupling behavior and the need to reduce computational cost, the FEM model of the LAMSC considers only its interior air domain (for a detailed discussion, refer to Note S2 in the ESM). To better represent the acoustic field conditions of the impedance tube used for evaluating acoustic performance in Section 3.2, the LAMSC was placed inside a cylindrical air domain serving as a waveguide tube, comprising an incident field and a transmitted field. The air domain within the submillimeter channels of the LAMSC was modeled using the thermoviscous acoustics module, while the remaining air domain was modeled using the pressure acoustics module. At the interface between the two



**Figure 1** The proposed LAMSC for ultrabroadband sound insulation. Structural diagram of (a) the LAMSC and (b) the labyrinthine channels. Micrographs of (c) the main structure and (d) the housing obtained by EDF microscope. (e) The picture of the fabricated LAMSC.



**Figure 2** The theoretical and simulated prediction for the STL of the LAMSC. (a) FEM model of the LAMSC established via COMSOL. (b) Theoretical and simulated results for the STL of the LAMSC with 3-layer and 4-layer channels. (c) Theoretical and simulated results for the STL of the LAMSC with cross-sectional dimensions of 0.3 mm × 0.3 mm and 0.4 mm × 0.4 mm. (d) The simulated results of the STL using the Pressure Acoustics and Thermoviscous Acoustics modules. (e) Simulated radial distribution of the thermoviscous power dissipation density across the channels. (f) Average thermoviscous power dissipation density in the channels over 50–3000 Hz.

domains, the built-in acoustic-thermoviscous acoustic boundary was applied. Radiation boundary conditions were applied to the front and end surfaces of the waveguide tube to simulate the suppression of sound reflection by the porous materials at both ends of the impedance tube. The cylindrical sidewall of the model was set as sound hard boundaries (zero normal acceleration) to represent the rigid wall condition of the impedance tube used in the experiment. Then, a plane wave of 1 Pa was excited at the inlet of the waveguide tube, with a frequency sweep from 50 to 500 Hz in 50 Hz steps, and from 500 to 6000 Hz in 500 Hz steps. The STL of the LAMSC in the simulation was calculated as follows [16]

$$\text{STL} = 20 \lg [\text{PI}/\text{PT}] \quad (1)$$

where PI and PT denote the average sound pressures at the incident face and the transmission face of the LAMSC, respectively.

Furthermore, a theoretical model of the LAMSC was established to validate the accuracy of the FEM model. For facilitating the modeling, the LAMSC can be simplified as three-layer Helmholtz

cavities (Fig. S11(d) in the ESM), and then the resulting theoretical STL can be calculated by Note S3 in the ESM

$$\text{STL} = 20 \lg \frac{1}{2} \left| T_{11} + \frac{T_{12}}{Z_0} + Z_0 T_{21} + T_{22} \right| \quad (2)$$

where  $T_{11}$ ,  $T_{12}$ ,  $T_{21}$ , and  $T_{22}$  represent the elements of the transfer matrix for the LAMSC. Notably, the detailed derivation of the transfer matrix can be found in Note S3 in the ESM.

The effects of the cross-sectional dimensions and number of annular channels on the STL were investigated through simulations and theoretical analysis, as shown in Figs. 2(b) and 2(c). By fixing the channel cross-sectional dimensions at 0.4 mm × 0.4 mm, the simulated STL and theoretical STL for 3 and 4 annular channels were investigated, respectively (Fig. 2(b)). For the 3 channels, both the theoretical and simulated resonance peaks of the STL occur at 3000 Hz. With an increase to four channels, the resonance peaks in the theoretical and simulated results shift downwards by 800 and 1000 Hz, respectively. Additionally, the minimum STL at 50 Hz

increases by 1.78 and 3.81 dB, respectively. With the channel number fixed at three, varying the cross-sectional size from 0.3 mm × 0.3 mm to 0.4 mm × 0.4 mm shifted the resonance peak downward by 100 Hz theoretically and 200 Hz in simulation, accompanied by a decrease in minimum STL at 50 Hz of 7.21 and 3.31 dB, respectively (Fig. 2(c)). Notably, the Helmholtz resonance peaks in Figs. 2(b) and 2(c) are notably higher than those of conventional sound-insulating acoustic metastructures (< 1 kHz) [17, 19, 20, 22, 23, 25–27, 29], confirming the effectiveness of the submillimeter-scale concentric annular channels in elevating the resonance frequency. Although increasing the number of annular channels and reducing their cross-sectional dimensions can yield a higher STL, this improvement comes at the expense of compactness and introduces greater fabrication difficulty and cost. Therefore, the channel number is confirmed as 3, and the cross-sectional dimension of the channel is set to 0.4 mm × 0.4 mm. The detailed structural parameters of the LAMSC are summarized in Table 1. Here,  $t$  and  $d$  denote the sidewall thickness of the labyrinth channels and the diameter of the circular outlet, respectively;  $d_i$  ( $i = 1, 2, 3$ ) represents the centerline diameter of the labyrinth channels in the  $i^{\text{th}}$  layer.

To verify the presence of thermoviscous losses at low frequencies and their contribution to enhanced sound insulation, the STL was simulated separately using the thermoviscous acoustics and pressure acoustics modules (Fig. 2(d)). Notably, the thermoviscous acoustics module incorporates thermoviscous damping within the annular channels, whereas the pressure acoustics module does not. As shown in Fig. 2(d), when thermoviscous losses are neglected, the minimum STL at 50 Hz is only 5.78 dB, with a fluctuation of 31.13 dB across 50–3000 Hz. In contrast, when thermoviscous losses are not neglected, the STL increases to 24.55 dB at 50 Hz, while the fluctuation in the same frequency band is reduced to 13.26 dB. It is evident that the enhancement of STL by the thermoviscous effect diminishes with increasing acoustic frequency. Using Eq. (S34) in the ESM, the mass-law predicted STL of the LAMSC is obtained, as shown in Fig. 2(d). It can be seen from Fig. 2(d) that, in the frequency range from 50 Hz to 3 kHz, the simulated STL without considering thermoviscous losses in the labyrinth channels is close to the mass-law predicted STL. This indicates that the excellent low-frequency sound insulation of the LAMSC relies on the thermoviscous losses within the submillimeter channels. To further elucidate this behavior, the thermoviscous power dissipation density within the annular channels of the LAMSC was simulated over the 50–3000 Hz range. The results indicate that thermoviscous losses primarily occur near the channel sidewalls, at the side holes, and around the outlet (Fig. 2(e) and Fig. S4 in the ESM). As the frequency rises, the thickness of the thermoviscous boundary layer decreases. Correspondingly, the average thermoviscous power dissipation density in the channels declines from 0.58 to 0.04 W/m<sup>3</sup> (Fig. 2(f)). This trend explains the frequency-dependent improvement in STL that is attributed to thermoviscous losses (Fig. 2(d)). In other words, the thermoviscous losses in the sub-millimeter channels effectively address the narrow

bandwidth and poor flatness of conventional sound insulation metastructures at low frequencies.

### 3.2 Acoustic performance of the LAMSC

To validate the sound insulation performance of LAMSC, normal-incidence transmission measurements were conducted using an impedance tube (Fig. 3(a)). Considering the reduced accuracy of impedance tube measurements below 100 Hz, acoustic performance is reported only above this frequency. With regard to the need of ensuring acoustic plane-wave conditions, a large-diameter tube with an inner diameter of 100 mm was employed for the 100–1600 Hz range, while a small-diameter tube with an inner diameter of 29 mm was used for 1600–6000 Hz. To address the diameter mismatch between the impedance tube and the LAMSC, the LAMSC was embedded in a 2 cm-thick metal fixtures made of 304 stainless steel, which was then placed inside the impedance tube. The fixtures were machined with an array of through-holes, each accommodating one LAMSC. The positional relationship among the LAMSC, the metal fixture, and the impedance tube is illustrated in Fig. S5 in the ESM. It is worth noting that the central through-hole of the metal fixture and the LAMSC were machined to ensure a transition fit, while the sidewalls of the LAMSC were evenly coated with Vaseline to prevent acoustic leakage. Porous material was placed at both ends of the impedance tube to absorb sound waves, thereby minimizing acoustic reflections. During the experiment, a loudspeaker at the front of the tube, driven by a signal analyzer and power amplifier, generated the acoustic signals. Four microphones are mounted on the impedance tube, with two dedicated to capturing the sound signals in the incident field and the other two for the transmitted field. The signals collected by the microphones were then fed back to the signal analyzer and the personal computer (PC) for calculating STL values according to the ASTM E2611 standard.

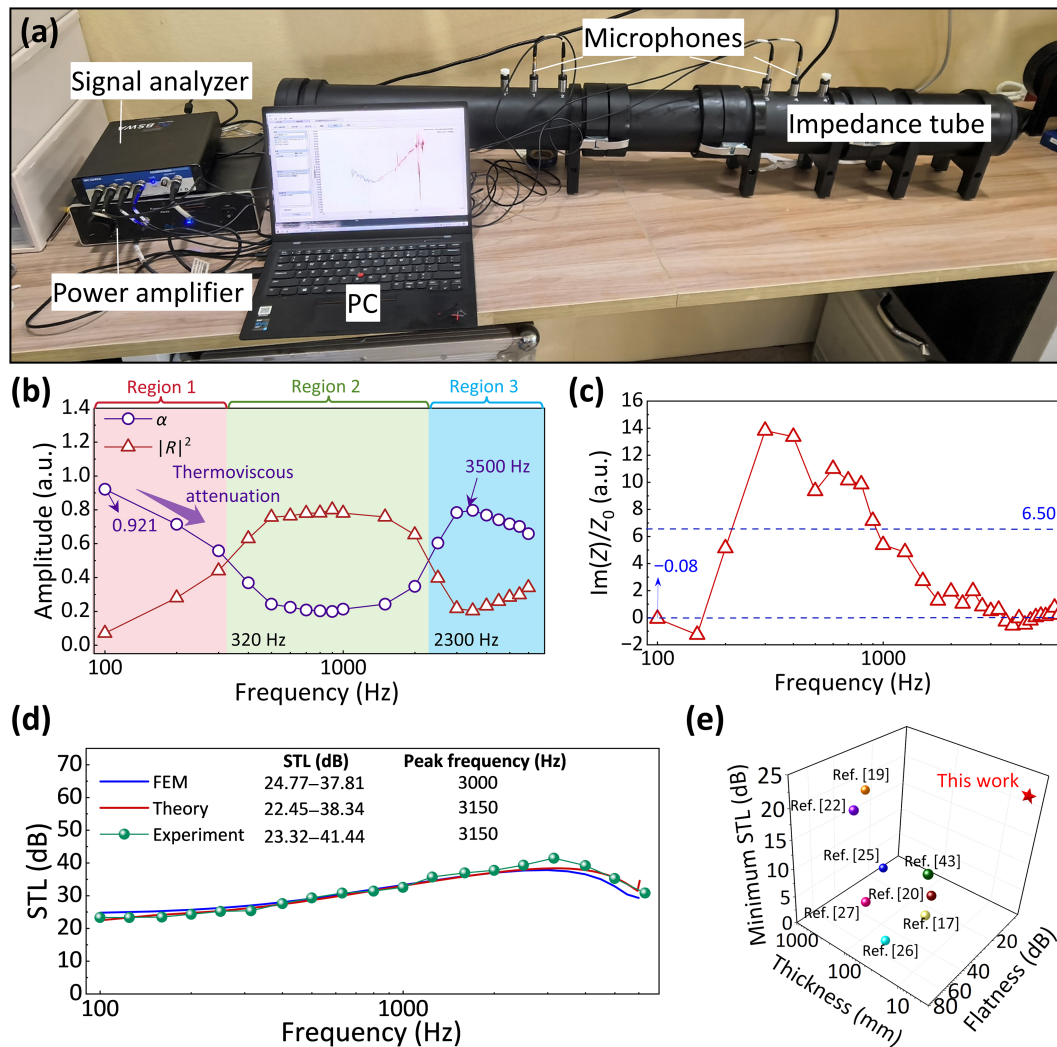
Based on the aforementioned experimental setup, the transmission ( $T$ ) and reflection coefficients ( $R$ ) of the LAMSC were characterized within the frequency range of 100–6000 Hz. Then, to quantify the absorption of incident acoustic signal by the LAMSC, the absorption coefficient  $\alpha$  was obtained (Fig. 3(b)), which is defined as [41, 42]

$$\alpha = 1 - |R|^2 - |T|^2 \quad (3)$$

Referring to Fig. 3(b), over the frequency range of region 1, the absorption coefficient remains at a high level, with a maximum value of 0.921. To further analyze the mechanism underlying the high absorption coefficient, the normalized imaginary part of the acoustic impedance ( $\text{Im}(Z)/Z_0$ ) was measured (Fig. 3(c)). It should be noted that  $Z_0$  represents the acoustic impedance of air. According to Fig. 3(c), the normalized acoustic impedance at 100 Hz is −0.08, confirming that the impedance mismatch is limited and allows incident sound waves to enter the LAMSC. Meanwhile, as the frequency increases, the absorption coefficient gradually decreases, which is consistent with the variation trend of thermoviscous power dissipation density observed in

**Table 1** Structural parameters of the LAMSC

| Parameters  | $D$ | $L$ | $w_1$ | $w_2$ | $h$ | $t$ | $d$ | $d_1$ | $d_2$ | $d_3$ | $d_4$ |
|-------------|-----|-----|-------|-------|-----|-----|-----|-------|-------|-------|-------|
| Values (mm) | 9.5 | 2.3 | 0.4   | 0.4   | 0.4 | 0.3 | 0.3 | 3.1   | 4.5   | 5.9   | 2.1   |



**Figure 3** Experimental results of the acoustic performance. (a) Photograph of the experimental setup based on impedance tube. The experimental results of (b) absorption coefficient, reflection coefficient and (c) the imaginary part of acoustic impedance. (d) Comparison between theoretical, simulated, and experimental results of STL. (e) Comparison with the comprehensive performance of sound insulation metastructures previously reported in the literatures (including minimum STL, flatness of the STL curve, and normal thickness of the structure) [17, 19, 20, 22, 25–27, 43].

aforementioned Fig. 2(f). Therefore, the sound insulation performance of the fabricated LAMSC in this frequency band is primarily dominated by thermoviscous dissipation. As acoustic frequency goes within the region 2, the acoustic reflection caused by the LAMSC is stronger than absorption. As shown in Fig. 3(c), the average value of  $\text{Im}(Z)/Z_0$  in this frequency range is as high as 7.64. This finding aligns with the established theory that a large positive imaginary part of impedance leads to strong wave reflection [44], further confirming the dominant role of acoustic reflection. Subsequently, for the frequency range of region 3, the absorption coefficient achieves a peak frequency of 3500 Hz, which closely matches the result in Fig. 2(c). Furthermore, within this band,  $\text{Im}(Z)/Z_0$  fluctuates near zero, which is consistent with the behavior of acoustic metastructures operating near resonance reported previously [45]. This phenomenon proves that the sound insulation in the region 3 is mainly governed by the Helmholtz resonance of the LAMSC.

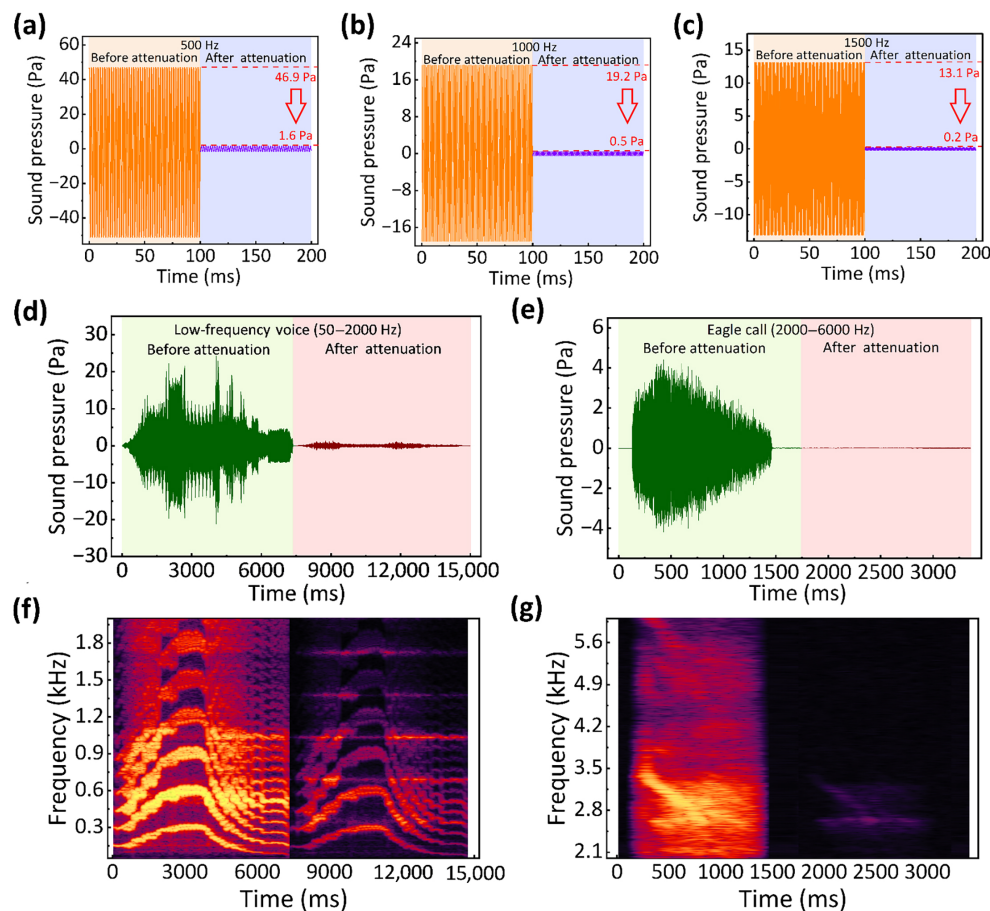
In fact, the contributions of thermoviscous dissipation, acoustic reflection, and structural resonance together enable the ultrabroadband sound insulation performance of the LAMSC. To

validate the sound insulation performance, the STL responses of the LAMSC were obtained through simulation, theoretical modeling, and experimental measurement, respectively (Fig. 3(d)). Over the frequency range of 100–6000 Hz, the simulated and theoretical STL values lie in the ranges of 24.77–37.81 and 22.45–38.34 dB, respectively, while the measured STL varies from 23.32 to 41.44 dB. Additionally, the measured STL in the low- and mid-frequency range (100–2000 Hz) exhibits the fluctuation of –9.23 to 5.20 dB relative to the value at 1 kHz (32.54 dB), corresponding to the flatness of 14.43 dB (the calculation method can be found in Note S5 in the ESM). The close agreement of the first resonance peaks of the STL curves from simulation (3000 Hz), theory (3150 Hz), and experiment (3150 Hz) further validates the accuracy and reliability of the theoretical and simulation models in this work. However, below the measured resonance frequency, the experimental STL values are slightly lower than those from simulation and theory. This discrepancy can be attributed to practical limitations in achieving ideal conditions, such as machining tolerances of the annular channels, non-ideal background acoustic fields, and boundary condition [26].

A comparison of the minimum STL, the flatness across 100–2000 Hz, and the normal thickness of our LAMSC with previous typical reflective-type and absorptive-type sound-insulating metastructures is presented in Fig. 3(e) and Table S1 in the ESM [17, 19, 20, 22, 25–27]. Notably, the normal thickness refers to the dimension of the metastructures along the direction of sound incidence. Despite a slightly higher minimum STL (25 dB) for the metastructure in Ref. [19], the developed LAMSC shows superior overall performance in terms of sound insulation, curve flatness, and structural miniaturization. According to the mass law [46], the STL of the sound-insulating structure is closely related to both the acoustic frequency and the structural thickness. To enable a fair comparison among different metastructures, the normalized STL was calculated by Eq. (S34) and Note S6 in the ESM for both the present work and literature structures (Table S1 in the ESM) [17, 19, 20, 22, 25–27, 43]. The results indicate that the normalized STL of the fabricated LAMSC exceeds the maximum values of these structures by  $\sim 2.9$  times, despite being nearly an order of magnitude thinner than the typical metastructures [17, 19, 20, 22, 25–27]. Besides, at a typical frequency of 1000 Hz, the thickness-to-wavelength ratio of the LAMSC is 1/149. In other words, the thickness of the LAMSC in the direction of sound transmission is on the deep subwavelength scale [47, 48]. These findings collectively demonstrate that the LAMSC achieves combined advantages in sound insulation, flatness, and structural compactness.

To visually demonstrate the sound insulation performance of the

LAMSC across the 100–6000 Hz frequency range, acoustic signals, including single-frequency signals and composite audio signals, were generated using a loudspeaker in the impedance tube, while microphones recorded these signals in the transmission field with and without the installation of LAMSC (Fig. 4). The results confirm that the LAMSC significantly attenuates single-frequency sounds at 500, 1000, and 1500 Hz, with the sound pressure reduced by factors of 28.3, 37.4, and 64.5, respectively (Figs. 4(a)–4(c)). Additionally, the sound insulation capabilities of the LAMSC were tested for low-frequency human voices and eagle calls, thereby confirming its potential for applications in the range of 100–6000 Hz (Figs. 4(d) and 4(e)). The time-domain signals in Figs. 4(d) and 4(e) were subjected to short-time Fourier transform (STFT) and fast Fourier transform (FFT) analysis (Figs. 4(f) and 4(g) and Fig. S6 in the ESM), further illustrating the specific sound insulation effects at various frequencies of the composite audio. It is noteworthy that in Fig. 4(f), the spectrograms of low-frequency voice before and after attenuation preserve relative intensity relationships across the different frequency components. This phenomenon can be attributed to the relatively flat STL curve of the fabricated LAMSC in the frequency range of 100–2000 Hz. To provide a more intuitive demonstration, the data collected before and after sound insulation in Figs. 4(a)–4(e) were converted into a video, presented as Video S1 in the ESM. It can be clearly determined that the LAMSC can not only achieve significant attenuation of both single and composite audio frequencies, but also maintain consistent audio



**Figure 4** The time history of the measured sound pressure collected by microphone at the transmission field of the impedance tube before and after the installation of LAMSC. (a)–(c) Single-frequency signals at 500, 1000, and 1500 Hz, respectively. ((d) and (e)) The time histories and ((f) and (g)) the corresponding STFT-processed frequency spectrum of the composite audio signals for low-frequency human voices (50–2000 Hz) and eagle calls (2000–6000 Hz).

quality before and after attenuation. These results are closely related to the exceptional sound insulation capability and flatness of the LAMSC.

### 3.3 The effect of the earplug with LAMSC on the $\alpha$ -EEG of participant

Benefiting from the combined strengths of the LAMSC in sound insulation and miniaturization, it was integrated into earplugs to further validate noise attenuation performance (Fig. S7 in the ESM). The earplug consists of three main components: the LAMSC, a frame made of PLA, and a cushion made of polyurethane foam. The LAMSC and the frame were bonded using epoxy resin adhesive, thereby preventing acoustic leakage between the two components. Since a narrow acoustic channel inside the frame would attenuate the acoustic signal, the diameter of the acoustic channel was designed to be 3 mm. The simulation using thermoviscous acoustics module confirms that the STL of the earplug frame itself does not exceed 0.8 dB (more details can be found in Fig. S8 in the ESM). In other words, the acoustic insulation of the earplug with LAMSC primarily originates from the LAMSC, while the attenuation induced by the frame is negligible.

Previous studies have indicated that exposure to traffic noise, whether short-term or long-term, is significantly associated with annoyance [49, 50]. To assess the level of annoyance,  $\alpha$  frequency band of EEG is commonly used as an analytical tool [49, 51, 52]. Specifically, as annoyance increases and cerebral stress levels correspondingly rise,  $\alpha$  oscillatory activity is suppressed, leading to a decrease in  $\alpha$  power, which is given by the following equation [49]

$$\alpha \text{ power} = \frac{\sum_{m=1}^{29} \sum_{n=8}^{13} |\text{FFT}_{mn}^2|}{29} \quad (4)$$

where  $m$  represents the number of channels of the electrode cap, and  $n$  is the frequency points in the FFT spectrum.

Then, to objectively evaluate the noise-reduction performance of earplugs equipped with LAMSC, EEG responses were recorded from the participant exposed to traffic noise at different SPLs (Fig. S9 in the ESM). The EEG measurement procedure relates to device wearing and relaxation, data acquisition, and data pre-processing (Fig. 5(a)). The participant was firstly fitted with the electrode cap and then instructed to relax in order to mitigate potential influences from prior environmental exposure. After that, EEG data were collected from the participant wearing earplugs with LAMSC and without LAMSC. Throughout the experiment, the participant was exposed to traffic noise (100–6000 Hz) presented at varying SPLs (45–75 dB). Note that each noise stimulus lasted 5 min, and a 5-min period without sound was inserted between successive noise exposures to eliminate the influence of previous exposures on participant's annoyance level. Finally, the 5-min EEG recorded under each sound pressure level would be divided into five consecutive 1-min segments to strengthen the evidence for the earplugs' noise-mitigation effect. Subsequent data processing steps included channel localization, filtering, artifact removal using independent component analysis (ICA), re-reference, epoching, and averaging of the epochs. For detailed data processing methods, please refer to Section 2.

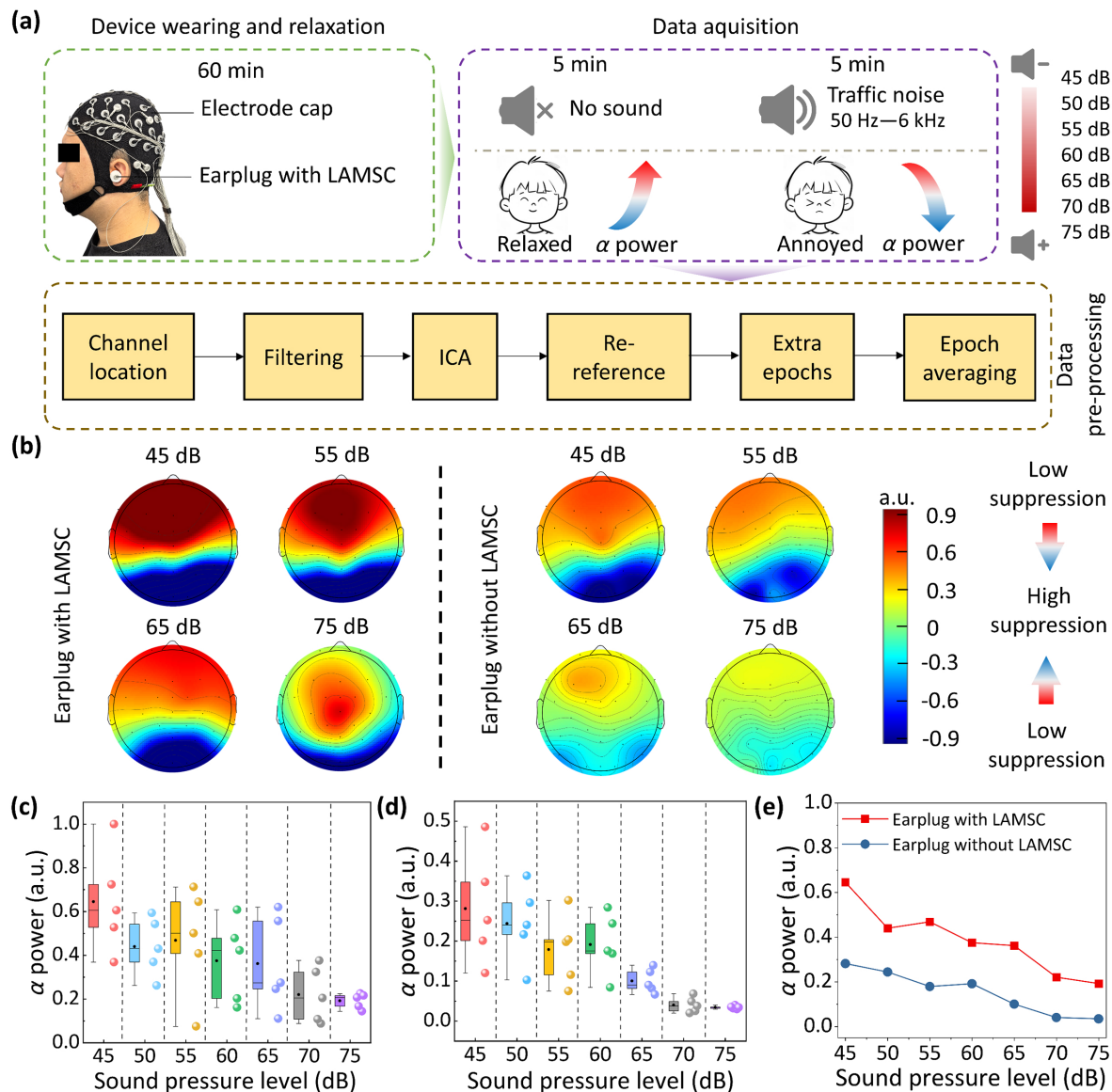
Figure 5(d) presents the topographic maps of  $\alpha$ -EEG for the participant exposed to traffic noise at different SPLs, comparing conditions with and without the LAMSC-equipped earplugs. While wearing the LAMSC earplugs, the plot at SPL of 65 dB appears

notably shallower than that at 45 dB, indicating pronounced suppression of  $\alpha$ -oscillatory activity. This suppressive effect becomes even more evident at SPL up to 75 dB. In contrast, when the participant used the earplugs without LAMSC,  $\alpha$ -oscillatory activity was remarkably suppressed at SPL as low as 45 dB. To quantify the noise-induced suppression of  $\alpha$ -oscillatory activity, the  $\alpha$  power was calculated based on Eq. (4) for both earplug conditions (Figs. 5(c) and 5(d)). The  $\alpha$ -power distributions across adjacent SPLs show overlapping ranges, which may reflect fluctuations in attentional state across different time periods [53]. Nevertheless, as the SPL increases, the overall  $\alpha$ -power exhibits a gradual decline, accompanied by a narrowing of its distribution range. This trend can be attributed to the stronger influence of traffic noise with increasing SPL. To visually compare the sound insulation performance of the LAMSC, the mean  $\alpha$ -power under each SPL condition in Figs. 5(c) and 5(d) was extracted and replotted in Fig. 5(e). Compared to the earplugs without LAMSC, the mean  $\alpha$ -power was consistently higher for the LAMSC-equipped earplugs across SPL of 45–75 dB. Furthermore, the mean  $\alpha$ -power (0.28) at SPL of 45 dB remains lower than that (0.36) at SPL of 65 dB, indicating that the LAMSC provides at least 20 dB of noise reduction. To validate this conclusion more rigorously, we further constructed an FEM model coupling the human ear canal with the LAMSC (Note S7 in the ESM). The simulation results show that the LAMSC exhibits an average STL of 29.68 dB for the human ear canal, which is consistent with the prediction from the EEG experiment. Thus, the superior noise-reduction performance of the LAMSC-assisted earplug further highlights the compact structure and ultrabroadband sound insulation of the developed LAMSC.

## 4 Conclusions

In summary, we developed an ultrathin labyrinthine acoustic metastructure with overall dimensions of 9.5 mm  $\times$  2.3 mm (diameter  $\times$  thickness), incorporating three annular channels with a cross-sectional dimension of 0.4 mm  $\times$  0.4 mm. Acoustic tests confirm the sound insulation performance of the LAMSC resulting from multiple synergistic mechanisms: thermoviscous absorption (dominant in region 1), acoustic reflection (dominant in region 2), and acoustic absorption induced by structural resonance (dominant in region 3). Compared with previously reported reflective-type and absorptive-type sound-insulating metastructures, the proposed device exhibits overall advantages in terms of thickness (2.3 mm), STL (23.32–41.44 dB@100–6000 Hz), and flatness within 100–2000 Hz (14.43 dB). Moreover, by evaluating the EEG alpha band of participant wearing earplugs with the LAMSC, at least 20 dB of noise attenuation by the LAMSC was confirmed. This work provides a new solution for the design and modeling of ultrabroadband compact sound insulation metastructures, which are expected to be applied in space-constrained scenarios for noise isolation.

**Electronic Supplementary Material:** Supplementary material (fabrication of the LAMSC, theoretical modeling of the metastructure, impact of channel geometry on thermoviscous losses and Helmholtz resonance, calculation of the flatness, definition of the normalized STL, and so on) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909075>.



**Figure 5** Evaluating noise reduction of LAMSC-based earplugs using  $\alpha$  power of EEG. (a) The flow chart of EEG data acquisition under traffic noise stimuli at different SPLs. (b) The typical topographic distribution of  $\alpha$ -EEG under different SPLs. Measured absolute power of  $\alpha$ -EEG by the tester wearing the earplugs (c) with LAMSC and (d) without LAMSC. (e) The average values of  $\alpha$ -EEG data in (c) and (d).

### Data availability

The data for all the work is available from the corresponding authors based on reasonable requests.

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### Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

### Author contribution statement

Y. L.: Conceived the idea, conducted the experiments, and wrote the manuscript. C. L.: Conceived the idea, analyzed the data, revised the original draft and supervised the study. Y. S.: Conceived the idea, conducted the experiments, and revised the final manuscript. Z. W.: Analyzed the data, supervised the work, and revised the final manuscript. Y. H. N. and H. Z.: Conducted the experiments. W. T. L.: Revised the original draft. S. C. F.: Supervised the study. All the authors discussed the results and revised the final manuscript.

### Use of AI statement

None.

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