Ultra-open High-efficiency Ventilated Metamaterial Absorbers with Customized Broadband Performance

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Abstract

In the last decades, the ongoing advances in acoustic metamaterials have unlocked unprecedented possibilities for manipulation of sounds. For example, to overcome the intrinsic limits of natural absorbing materials when dealing with low-frequency sounds (<1000 Hz), various acoustic metamaterial absorbers have been proposed.
However, the rigid trade-off between absorption and ventilation performances definitely constrains their applications in many scenarios where free flows of fluids are necessary. Here, a compact ventilated metamaterial absorber is designed using coupled split-tube resonators aiming at low-frequency sounds. The absorber, in experiments, simultaneously ensures high-performance absorption and ventilation. Their mechanism is understood from an effective model of coupled lossy oscillators. Furthermore, the absorbers can be simply stacked to work in a customized broadband, while still maintaining a good ventilation. The demonstrated absorber provides a clear scheme for achieving high-performance absorption and ventilation at low frequencies and could find practical applications in noise-control scenarios with free flows.

1. Introduction

In the last two decades, various acoustic metamaterial absorbers have been proposed to overcome the intrinsic limits of natural sound absorbing materials, when dealing with low-frequency sounds (<1000 Hz) [1-4]. Once transmissions are blocked, they give rise to high-efficiency absorptions at customized working frequencies with compact profiles [5-13]. Compared with conventional porous materials, they can be deployed in harsh environments such as humid and narrow spaces to control the noise and improve the sound environment. However in daily life and industry, the generation of noise is usually associated with the instabilities of background flows, especially the turbulences in or around ducts, nozzles and turbines [14-18]. Moreover, the fluids must have a free pass for the proper functioning of corresponding devices,
apparatus or facilities. Such practical scenarios render many previous metamaterial absorbers incompetent, because they usually need to completely seal flow channels to eliminate transmissions. Otherwise, if there is a transmission channel, the absorption could be drastically reduced and often cannot exceed 50% [19,20]. Recently, several ventilated metamaterial absorbers have been demonstrated [21-28]. However, their performances, including working frequency, bandwidth, and maximum absorption, are still not satisfying compared with ventilated sound barriers [21,29-35], some of which can simultaneously achieve high-efficiency sound reflection (>90%) and ventilation (>60%) at low frequencies. This performance deficiency can be ascribed to the fact that the maximum absorption cross-section of a single subwavelength scatter is only one quarter of its maximum scattering cross-section [28,36]. Accordingly, the absorption of a ventilated acoustic metamaterial composed of subwavelength scatters is usually small compared with its reflection. Despite the odds, is it still possible to break the limit and finally achieve a broadband absorber with high-efficiency absorption and ventilation? If so, the designed absorber would have many important applications in noise control of ducts, nozzles, and turbines. Many stunning structures, such as silencer windows, will also become possible, and can provide good daylight, fresh air, and a silent environment.

In this work, an ultra-open ventilated metamaterial absorber (UVMA) is demonstrated (see also Movies S1-S5 in Supplementary Information), which can concurrently achieve high-efficiency acoustic absorption (>95%) and ventilation (>80% wind velocity ratio). The UVMA unit is comprised of weakly coupled split-tube
resonators, and its absorption is demonstrated through numerical calculations and experimental measurement. Broadband absorption is then achieved by optimized stacking of UVMA units with different resonance frequencies. Thus, the demonstrated metamaterial absorber provides a direct route for simultaneously achieving high-efficiency absorption and ventilation at low frequencies and may find practical applications in noise-control engineering of an environment filled with flowing fluids such as air conditioners, exhaust hoods, and flow ducts.

2. Materials and Methods

2.1. Fabrication of UMVA Units

The UVMA units are fabricated using the 3D printing technique; more specifically, stereolithography (SLA) of a commercial photopolymer resin (Somos 14120, DSM, Netherland) is used in the fabrication. The 3D printer (iSLA660, ZRapid Tech, China) has an accuracy of 0.1 mm, and the cured resin has a tensile modulus of 2.46 GPa and a density of 1.10 g/cm³.

2.2. Setup of Simulations

All full-wave simulations are performed using COMSOL Multiphysics, a commercial finite element method (FEM) solver. Coupled modules of Pressure Acoustics and Thermoacoustics are used. The thermal and viscous losses inside the UVMA units are naturally included in Thermoacoustics module. In all simulations, the 3D-printed photopolymer resins are treated as acoustic hard boundaries, while the material parameters of air are set as follows: density 1.2 kg/m³, dynamic viscosity
18.5 μPa, thermal conductivity 24 mW/(m·K), specific heat ratio 1.4, thermal expansion coefficient $3.41 \times 10^{-3}$ K$^{-1}$, and speed of sound 343 m/s. No tunable auxiliary parameters exist in the simulations.

2.3. Setup of Impedance Tube

All acoustic measurements are performed in a square impedance tube using the general four-microphone two-load method [26,37]. The impedance tube (schematically depicted in Fig. 1(e)) is comprised of two aluminum square tubes (inner cross section of 147×147 mm$^2$, tube thickness 5 mm), a full-range speaker (M5N, HiVi, China), four microphones (MP418, BSWA, China), a power amplifier (ATA 304, Aigtek, China), and a data acquisition analyzer (MC3242, BSWA, China). The plane wave cutoff frequency of the aluminum tubes is ~1100 Hz. The lengths of the two aluminum tubes are 600 mm and 400 mm, respectively. A clamped aluminum plate of thickness 4 mm is employed as the rigid back to model acoustic hard-boundary termination. After removing the aluminum plate, the sound in the tube will radiate outside that models an acoustic open boundary termination. They serve as two different termination loads in the measurement. Photographs of the impedance tube are shown in Fig. S4 (see Supplementary Information).

2.4. Setup of Ventilation Measurement

Ventilation efficiency of the UVMA units are characterized using a measurement system [29] comprised of two aluminum square tubes (inner cross section of 147×147 mm$^2$, tube thickness of 5 mm) with a length of 200 mm and an electric fan (SF2-2, HEYUNCN, China) with a maximum air volume of $3.7 \times 10^3$ m$^3$/h. An anemometer
(TM856, TECMAN, China) is used to monitor the air flow velocities at the outlet of the aluminum tube, while the electric fan is placed at the inlet, as shown in Fig. 5(a). The air gap between the electric fan and the tube are sealed with sponges. We use the wind velocity ratio \( VR \) to characterize the ventilation performance defined as the ratio between the measured air velocities with and without the sample \( VR = \frac{v_{\text{air,w}}}{v_{\text{air,wo}}} \). Here, \( v_{\text{air,w}} \) and \( v_{\text{air,wo}} \) refers to the average flow velocity at the outlet with/without the sample placed between the aluminum tubes, respectively. Moreover, to improve the measurement reliability, the air flow velocities are recorded at the positions 1–9 of the outlet (as shown in the inset of Fig. 5(a)). The readings on the anemometer are averaged to obtain the final data. The inlet air flow velocities are varied by tuning the power of the electric fan, such that different pairs \( (v_{\text{air,w}}, v_{\text{air,wo}}) \) of the averaged air flow velocities are obtained and are used to calculate the wind velocity ratio \( VR \). Photographs of the ventilation measurement system are shown in Fig. S5 (see Supplementary Information). A direct view of the measurement system inside the tube is also given in Movie S5 (see Supplementary Information).

3. Results and Discussion

3.1. Structure of UVMA Metamaterial Absorber

An array of the UVMA units are assembled as a frame constituting the designed metamaterial absorber, as schematically depicted in Fig. 1(a). The hollows in the frame permit the flow of various fluids such as air or water, freely passing through the structure. In the following study, it is assumed that the structure is immersed in air.
The sound wave incident on the UVMA units should be absorbed near perfectly, thus simultaneously realizing the efficient absorption and ventilation. As demonstrated, the UVMA units are packaged in a rectangular lattice, and the lattice constants along the $x$ and $y$ directions are $L$ and $L/4$, respectively. A supercell comprising of four UVMA units is depicted in Fig. 1(b), and the details of a single UVMA unit are shown in Fig. 1(c). The cover is removed to demonstrate the details of the UMVA unit (note that the structure is rotated by $90^\circ$ for better visualization). Each UVMA is composed of two split-tube resonators, placed symmetrically and coupled through a narrow slit between them [6,26]. The sectional diagram on the $xz$-plane for a single UVMA unit is presented in Fig. 1(d), demonstrating the identical but oppositely oriented split-tube resonators. Working at low frequencies, the proper geometric parameters of the UVMA units are determined, such that the units should have optimized absorption and ventilation, and we summarize possible design strategies in Section 3.2. Experimental verifications are then conducted, with the setup shown in Fig. 1(e), which will be discussed in Sections 3.3 and 3.4. The ventilation performance of the metamaterial absorbers will be discussed in Section 3.5.
Figure 1. (a) Perspective schematic of the UVMA units arranged in a rectangular lattice. The lattice constant along $x$ ($y$) direction is $L$ ($L/4$). (b) Close-up view of a supercell. It is comprised of four UVMA units. (c) Perspective view of a single UVMA, as denoted by the dashed rectangle in (b). To demonstrate the details inside, the structure is rotated and the cover is removed. (d) Sectional schematic of the UVMA on the $xz$-plane. (e) Experimental setup for acoustic measurement. The impedance tube has a square cross-section ($147 \times 147$ mm$^2$), and the standard four-microphone method is adopted. The inset shows the photograph of a fabricated sample placed in
the impedance tube.

3.2. Numerical Study of UVMA Design Strategies

To investigate the impact of geometric parameters on the acoustic absorption performance of the UVMA, full-wave numerical simulations are performed (see setup in Section 2.2). Complex transmission coefficient $t$ and reflection coefficient $r$ are retrieved, and the absorption coefficient $A$ is calculated as $A = 1 - |t|^2 - |r|^2$, due to the conservation of energy. The key geometric parameters (denoted in Fig. 1(b)–(d)) are the length $a$, height $b$, width of the channels $w_{\text{chan}}$, and width of the slits $w_{\text{slit}}$, which effectively alter the acoustic performance of the UVMA.

First, the length $a$ is considered while fixing the other parameters ($b = 40$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm). The calculated absorption is plotted as a 2D color map of the length $a$ and the frequency, as shown in Fig. 2(a). The red strip in the color map highlights the shift of the resonance of the UVMA unit. As the length $a$ is increased, the resonance shifts towards lower frequencies, and the absorption reaches near-unity. Next, the height $b$ is considered, which controls the UVMA's open area ratio while fixing other geometric parameters. The corresponding absorption is plotted versus $b$ and frequency, as shown in Fig. 2(b). The height $b$ (25–60 mm) considered here corresponds to the open area ratio of 59–83%. Similarly, as the height $b$ increases while the open area ratio decreases, the resonance shifts towards lower frequencies, and the absorption also reaches near-unity.

The cases are more interesting for the widths of the channels $w_{\text{chan}}$ and slits $w_{\text{slit}}$. 9
as shown by the corresponding absorption color maps displayed in Figs. 2(c) and (d), respectively. It can be seen that with a decreasing width of the channels $w_{\text{chan}}$ or slits $w_{\text{slit}}$, the acoustic absorption of the UVMA improves significantly, and the resonance also shifts towards lower frequencies. More importantly, when $w_{\text{chan}}$ becomes small enough, the two moderate absorption resonances ($\sim 60\%$) will coalesce into a single near-unity peak. Thus, very narrow channels and slits (<2.0 mm) must be employed to ensure an efficient absorption. The coalescence and enhancement of the absorption resonances can be understood using an effective model of coupled lossy oscillators (see Note 1 in Supplementary Information).

Overall, it is shown that we can maintain the high-efficiency absorption (>80\%) of the UVMA units, meanwhile shifting its resonance in a large range, if only we keep the narrow channels $w_{\text{chan}}$ and slits $w_{\text{slit}}$ untouched. This fact suggests a possibility of optimizing the absorber for different working frequencies and ventilation conditions.
Figure 2. (a)–(d) Simulated spectra of absorption $A$ as the function of frequency and the geometric parameter $a$ (a), $b$ (b), $w_{\text{chan}}$ (c), or $w_{\text{slit}}$ (d), respectively. All Start from the configuration $a = 100$ mm, $b = 40$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm (when tuning one parameter, the others are kept unchanged). The red strips highlight the shift of resonances when the geometric parameters are tuned.

3.3. Experimental Demonstration of Acoustic Performance

Experimental measurement of acoustic properties of the UVMA units are then conducted. Two samples are considered and are labeled as Sample I ($a = 100$ mm, $b = 40$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm) and Sample II ($a = 150$ mm, $b = 45$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm). The open area ratio of Sample I (II) is 72.8% (69.4%). The
measured transmission and reflection of the two samples (dotted lines) are shown in Fig. 3(a), which agree well with the simulated results (solid lines). Both reflection and transmission spectra exhibit dips near the resonance frequencies, which implies high-efficiency absorptions. As shown in Fig. 3(b), the simulated and measured absorptions demonstrate quantitative agreement between each other. In experiments, for Sample I (II), the measured absorption reaches 93.6% (97.3%) at 637 Hz (472 Hz), as indicated by the red (purple) arrow. For reference, the acoustic performances of two melamine foams (Basotect G+, BASF, Germany) [26] are also measured. They are labeled as Foam I and Foam II, which have the same dimensions as Sample I and Sample II, respectively, and their absorptions are plotted as gray solid lines in Fig. 3(b). The UVMA units clearly demonstrate superior acoustic performances near the resonances compared to the commercial foams. This superiority is more clearly demonstrated if the data are plotted in the dB scale (see Fig. S1 in Supplementary Information), which are more industrially relevant [38]. This superiority is also straightforwardly manifested in the demonstration videos (see Movies S1 and S2 in Supplementary Information), where we can directly hear the absorption performance of Sample II and Foam II, respectively.

In order to understand the physical mechanism behind the high-efficiency absorption of the UVMA units at resonances, especially why it can significantly exceed 50%, the simulated cross-sectional acoustic pressure fields of Sample I are plotted. The pressure amplitude at the resonance (610 Hz) is shown in Fig. 3(c). Similar to a single split-tube resonator [6,26], the absorption of the UVMA is caused
by the friction of oscillating air flows in the long and narrow channels, which
dissipates the incident sound energy as heat. Since the air flow is driven by the
pressure difference between the inside cavities and the outside environment, the
UVMA can offer a significant absorption in the condition of no porous materials, as
the pressure difference is largely enhanced at resonance.

Moreover, the acoustic pressure of the two resonators at resonance demonstrates a
90°-phase difference, as shown in Fig. 3(d), which suggests that the mirror plane ($z = 0$)
could be treated as a superposition of acoustic soft and hard boundaries. The
comparison with the simulations involving a single split-tube resonator and an
acoustic soft or hard boundary confirms that this treatment is exact (see Fig. S3 in
Supplementary Information). Both acoustic hard and soft boundaries act as a back
reflecting surface, causing multiple scatterings of the incident sound that hybridize the
resonance mode of a single split-tube resonator. This hybridization is the key to
achieve an effective absorption [19,20]. Further, because the waves reflected by
acoustic hard and soft boundaries have a 180°-phase difference, they would tend to
cancel each other, ensuring a near-unity absorption [26]. The origin of this 90°-phase
difference at resonance can also be understood in the frame of the model of coupled
lossy oscillators (see Note 2 in Supplementary Information).
Figure 3. (a) Simulated (solid lines) and experimentally measured (dashed lines) transmission and reflection spectra of the UVMA units. For Sample I (open area ratio 72.8%), $a = 100$ mm, $b = 40$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm. For sample II (open area ratio 69.4%), $a = 150$ mm, $b = 45$ mm, $w_{\text{chan}} = 1.4$ mm, $w_{\text{slit}} = 1.4$ mm. (b) Simulated (colored solid lines) and experimentally measured (dotted lines) absorption spectra of Sample I and Sample II. Gray solid lines represent measured absorption spectra of melamine foams (Basotect G+, BASF, Germany). As a reference sample, Foam I (II) has the same dimensions as Sample I (II). (c), (d) Simulated pressure field maps for Sample I on the slice $y = 0$ (central cross section), when the frequency is at resonance (610 Hz). The pressure field in the resonators exhibit a strong enhancement (c), and a $90^\circ$-phase difference between the two resonators (d). The green arrows indicate the incident sound. The black scale bar is 20 mm.
3.4. Customized Broadband Acoustic Absorption

As discussed in the previous literature [38], the causal nature of an acoustic response imposes a fundamental inequality that relates the two most important aspects in sound absorptions: the absorption spectrum and the absorber length. However, only the no-transmission situation was considered, and what is the limit when transmission is allowed and an open area ratio is specified? It would clearly be complicated for a general case, but if the absorber is mirror symmetric, the open area can be treated as being terminated by the superposition of an acoustic soft boundary and an acoustic hard boundary (see Fig. S3 in Supplementary Information). Thus, the minimum length $a_{\text{min}}$ of the absorber should be twice the case when the transmission channel is blocked. That is, we have

$$a_{\text{min}} = \frac{1}{2\pi^2} \frac{B_{\text{eff}}}{B_0} \int_0^{\infty} \ln[1 - A(\lambda)] d\lambda,$$

where $B_0$ is the bulk modulus of the background fluid (air), $B_{\text{eff}}$ is the effective bulk modulus of the metamaterial in the static limit, $A(\lambda)$ is the absorption spectra, and $\lambda$ is the acoustic wave length [38]. For a broadband absorber comprised by finite number $(N)$ of absorbing units, their resonance frequencies should be exponentially spaced for optimal performance [38]. Therefore, the resonance frequencies should be selected as:

$$f_n = f_0 e^{\phi n},$$

where, $n = 1$ to $N$, $f_0$ is the cut-off frequency, and $\phi$ is a coefficient determined by the target frequency band. Broadband UVMA units are constructed in the targeted
frequency bands through this relationship. Given the trade-off between absorption and ventilation, and to maintain an efficient ventilation, a broadband UVMA comprised of seven units is considered (shown in Fig. 4(a)). As an example, the frequency band 478–724 Hz is targeted, and the resonance frequencies of the units are selected as 478 Hz, 512 Hz, 549 Hz, 588 Hz, 630 Hz, 676 Hz, and 724 Hz. The corresponding lengths $a$ of the units are determined by referring to Fig. 2(a). The simulated (solid line) and measured (dotted line) absorption spectra are shown in Fig. 4(b). The working bandwidth is 465–765 Hz in simulations (which is defined as the frequencies where the absorption exceeds 50%), corresponding to a large fractional bandwidth of 48.8%. Meanwhile in the experiments, the working bandwidth is 476–726 Hz, corresponding to a fractional bandwidth of 41.6% [12]. The designed absorber has successfully covered the targeted frequency band and the simulated (measured) average absorption in the band is 73.3% (69.3%). The small discrepancy can be attributed to the fabrication and measurement errors during the experiments in one aspect, and the assumption of infinite acoustic impedance for the solids in simulations in the other aspect. Nevertheless, with an open area ratio of 52.4%, the results confirm that the stacking scheme has led to a broadband UVMA.

There is an evident trade-off between the bandwidth and the average absorption. If a narrower frequency band is targeted instead (for example, 478–620 Hz), the absorption will be enhanced (Fig. 4(c)). With the selected closer resonance frequencies (478 Hz, 499 Hz, 521 Hz, 544 Hz, 568 Hz, 593 Hz, 620 Hz), the simulated (measured) average absorption in the targeted band becomes 85.8%.
Further, multiple discontinuous frequency bands can be aimed. For instance, considering the dual bands 478–550 Hz and 640–690 Hz, the resonance frequencies (478 Hz, 501 Hz, 525 Hz, 550 Hz,) are chosen for the first band, and (640 Hz, 665 Hz, 690 Hz) for the second band. The simulated (measured) absorption spectrum is shown in Fig. 4(d) and the average absorption in the dual bands is 83.1% (78.1%). The performance of the dual-band sample is also directly demonstrated (see Movies S3 in Supplementary Information). The results confirm that a UVMA can be designed with customized working frequency bands, meanwhile permitting the pass of sounds at required frequencies.

Figure 4. (a) Perspective schematic of a broadband UVMA comprised of 7 units (open area ratio 52.4%), with resonance frequencies increasing from units 1 to 7, and their
The stacking order is shown in the inset; (b)–(d) absorption of three samples denoted as Sample III (b), Sample IV (c), and Sample V (d), respectively. For Sample III, the 7 resonance frequencies are (478 Hz, 499 Hz, 521 Hz, 544 Hz, 568 Hz, 593 Hz, and 620 Hz). For Sample IV, the seven resonance frequencies are 478 Hz, 499 Hz, 521 Hz, 544 Hz, 568 Hz, 593 Hz, and 620 Hz. For Sample V (which deals with dual bands), the seven resonance frequencies are 478 Hz, 501 Hz, 525 Hz, 550 Hz, for the first band, and (640 Hz, 665 Hz, 690 Hz) for the second band. The blue scatters denote the distributions of the resonance frequencies.

### 3.5. Demonstration of High-Efficiency Air Ventilation

As mentioned in Section 2.4 (where the setup of the ventilation measurement are specified), the ventilation performance of the UVMA units are characterized by their wind velocity ratios [29,39,40], defined as the ratios between air flow velocities with and without the samples. First, Sample I is characterized (open area ratio 72.4%), which is sandwiched between the two aluminum tubes. The electric fan is placed at the tube inlet and the anemometer is placed at the outlet, as depicted in Fig. 5(a). The measured air flow velocities (black dots) with ($v_{\text{air,w}}$) and without ($v_{\text{air,wo}}$) the sample are shown in Fig. 5(b). It can be seen that they manifest a linear dependence, and the linear fitting (red line) gives a favorable wind velocity ratio ($VR$) of 81.8%. Likewise, the wind velocity ratio of Sample II (open area ratio 69.3%) is measured to be $VR = 76.6\%$, as shown in Fig. 5(c). A direct demonstration of its ventilation performance is also provided (see Movie S4 in Supplementary Information). Thus, it proves that the
design has achieved a high-efficiency ventilation while maintaining a near-unity low frequency sound absorption. Further, the broadband Sample III is considered (open area ratio 69.3%), and its measured flow velocities are shown in Fig. 5(d). In a similar manner, the linear fitting gives a favorable wind velocity ratio ($VR$) of 62.3%. Although the broadband UVMA decreases the open area ratio to some extent, it can still maintain a desirable wind environment.

**Figure 5.** (a) Schematic of the ventilation characterization system, which measures wind velocity ratios. The inset indicates the positions at the tube outlet where the air flow velocities are recorded. (c),(d) Averaged flow velocities at the outlet with ($v_{air,w}$) and without ($v_{air,wo}$) the samples, where the measured values (black dots) exhibit a good linear relation and can be well fitted (solid lines). The slopes of the fitted lines
give the wind velocity ratios (VR) of samples I (c) and III (d). As denoted in the figures, VR = 81.8% for sample I, VR = 76.6% for sample II, and VR = 62.3% for sample III.

4. Discussion

An ultra-open ventilated metamaterial absorber with customized broadband performance working at low frequencies is proposed and demonstrated. The absorber is comprised of weakly coupled split-tube resonators, which can simultaneously achieve high-efficiency absorption and ventilation with proper geometric parameters (see demonstration videos Movies S1-S5 in Supplementary Information, which directly shows its absorption and ventilation performances). The key to the absorption of the UVMA units is the small coupling between the two split-tube resonators, which leads to the merge of the resonance peaks of the symmetric and anti-symmetric modes. Due to the persistent high-efficiency absorption and the sensitive shift of the resonance frequency, the geometric parameters can be adjusted to achieve the required absorption performance. Through the theory of broadband absorption structure optimization and under the condition of maintaining efficient ventilation, exponentially distributed resonance modes are chosen to extend its absorption frequency to a broadband range. The absorber can also work in multiple discontinuous bands. This structure breaks the limits of previous acoustic absorbing metamaterials, achieving both high-efficiency acoustic absorption and ventilation, and can be extended to customized broadband working frequencies.

Therefore, the UVMA units should have promising application potential in a
variety of acoustic engineering scenarios, such as the noise control of turbines and duct systems. Although the UVMA units immersed in air is the only situation investigated, the design principle should also work for other background fluids, such as water.

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Author Contributions

X.W. and W.W. conceived the original idea. X.X., X.L., and X.W. performed the simulations. X.W. derived the theory. Y.H. and S.W. supported fabrication process of the samples. X.X. carried out the experiments. X.L., P.W., H.H. and Q.M. helped in the experiment setup. X.X. and X.W. analyzed the data, prepared the figures, and wrote the manuscript. X.W., Y.H., S.W. and W.W. supervised the project. All authors contributed to scientific discussions of the manuscript.

Additional Information

Supplementary Information is available in the online version of the paper.
Competing Financial Interests

The authors declare no competing financial interests.

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