A sound absorbing metasurface with coupled resonators

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An impedance matched surface is able, in principle, to totally absorb the incident sound and yield no reflection, and this is desired in many acoustic applications. Here we demonstrate a design of impedance matched sound absorbing surface with a simple construction. By coupling different resonators and generating a hybrid resonance mode, we designed and fabricated a metasurface that is impedance-matched to airborne sound at tunable frequencies with subwavelength scale unit cells. With careful design of the coupled resonators, over 99% energy absorption at central frequency of 511 Hz with a 50% absorption bandwidth of 140 Hz is achieved experimentally. The proposed design can be easily fabricated, and is mechanically stable. The proposed metasurface can be used in many sound absorption applications such as loudspeaker design and architectural acoustics. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4961671]

A perfect sound absorber with sub-wavelength dimensions is of great interest for scientists and engineers owing to its ability to convert acoustic energy to heat or other forms of energy. A high efficiency sound absorption device requires not only a proper mechanism of energy conversion but also an impedance matched surface to that of air, so that sound can efficiently enter the absorber. Conventional means of acoustic absorption use porous and fibrous materials,[1–3] gradient index materials,[4] or perforated or micro-perforated plates with cavities behind them.[3,5] Such absorbers usually result in an imperfect impedance match with the incoming wave, or are very bulky themselves, with dimensions comparable with the incoming wavelength. Active absorbers, on the other hand, require sophisticated control of the electrical systems, and thus are expensive and less robust. Coherent perfect absorbers in optics[6] achieve absorption by phase matching of counter-propagating waves. Its counterpart in acoustics[7] requires either acoustically thick materials or dissipative plates which require control over the loss of the material,[8] making it hard to implement. Also, no perfect absorption is experimentally achieved so far in such plates.

During the last decade, rapid development of acoustic metamaterials enables manipulation of acoustic waves and enhancement of acoustic absorption in unprecedented ways.[9–47] Some of the most successful approaches have been based on resonant absorption, a technique commonly used in acoustic design[48] particularly in the form of discrete resonant structures.[31,49] One noteworthy approach based on membrane-type acoustic metamaterials (MAMs) has been reported to yield perfect absorption at certain frequencies.[22–27] While effective and very thin, such a design requires uniform and controlled tension of the membrane, which imposes fabrication challenges. Also, MAMs are subject to creeping due to the tension in the membrane, causing durability issues.

In this letter, we design and demonstrate a type of acoustic metasurface that serves as a perfect absorber. Perfect absorption is achieved by converting the incident propagating wave to a non-radiating bound surface mode that dissipates the energy. By combining multiple Helmholtz resonators, we designed this nearly perfect sound absorber with a thickness of about $\lambda/20$, and over 99% energy absorption is observed in the experiment. Our metasurface can be easily fabricated using 3D printing, and is rigid and therefore functionally stable. By controlling the parameters of the resonators, we can create and make use of the hybrid resonant mode so that the average displacement component can be tuned to match the impedance of the background medium, making them "dark" to the incident sound. The experimental results and simulations are in good agreement. The idea of designing non-radiating hybrid resonant modes provides a way of designing acoustic absorbers.

To illustrate our idea of absorption from coupled resonators, we start from the two-resonator case. Note here that there is no fundamental difference from two or multiple resonators, although more than one resonator structure is necessary in order to create the required hybrid modes. Our metasurface is demonstrated in Fig. 1(a), and a normally incident plane wave is assumed. The building block of the metasurface consists of two parallel Helmholtz resonators with resonant frequencies slightly different from each other. They are designed with same cavity size, same neck length, but different neck width, as demonstrated in Fig. 1. Our design starts from the same resonators and gradually tunes one of the resonators by changing its neck width until total absorption is observed. Note here that more parameters can be tuned to optimize the absorber, such as bandwidth, but in this paper we are only focused on the physics. Detailed parameters of the design are shown in Table I with all units in mm. For an isolated oscillator, there is a π phase shift with respect to the excitation around the resonant frequency. Therefore, between the resonant frequencies of two resonators, when the incident plane wave hits the metasurface, two resonators will both have strong responses but with inverted phase. Since two resonators are placed close to each other, there will be a strong coupling between them. Coupling of these two resonators forms a combined resonant mode where both of them vibrate significantly with a phase difference of 180°. Because the distance between these two resonators are much smaller than the wavelength, the

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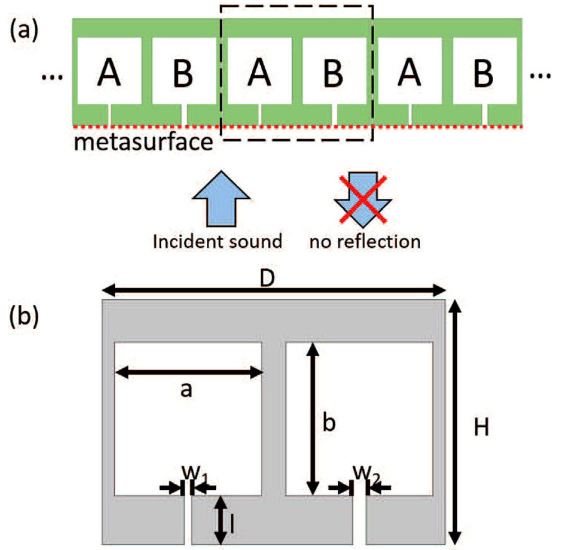

FIG. 1. Geometry and dimensions of the metasurface cell. (a) Schematic illustration of the metasurface and its unit cell, where A and B stand for different types of resonators; (b) Dimensions of the unit cell. Detailed parameters can be found in Table I.

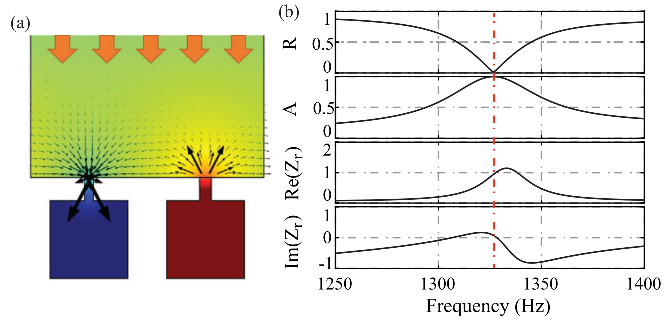

FIG. 2. Field distribution and absorption performance. (a) Pressure field and velocity field in the near field at "dark" frequency. (b) Reflection coefficient, absorption coefficient, and both real part and imaginary part of the relative impedance of the metasurface, demonstrating that the match of impedance from designed cells to the background media is key for achieving total absorption.

transverse wave number $k_\perp$ of the reflected wave will become much larger than k in the air, i.e., $|k_\perp| > 2\pi/\lambda$. Owing to the dispersion relation $k_\perp^2 + k_\parallel^2 = (2\pi/\lambda)^2$, $k_\perp$ becomes imaginary, where $k_\parallel$ denotes wave number along the surface and $k_\perp$ is wave number normal to the metasurface. In this case, the reflected wave will become evanescent and decays rapidly along the normal direction because of a large imaginary $k_\perp$, and thus the energy is efficiently bound to the metasurface.

Our design was verified with numerical simulations using commercial FEM package COMSOL Multiphysics. The simulations are performed in Pressure Acoustics module. The material is air with density $\rho_{air} = 1.25\,\mathrm{kg\,m^{-3}}$ and sound speed $c_{air} = 343(1 + \eta i)$, where η denotes loss in air. In our simulation, we set $\eta = 0.01$ to match experimental resonator bandwidth. Note that for a small η, there is no significant difference whether we incorporate the loss into density or bulk modulus. Since 3D printed samples are acrylonitrile butadiene styrene (ABS) plastic with density $\rho = 1180\,\mathrm{kg\,m^{-2}}$ and speed of sound $c = 2700\,\mathrm{m\,s^{-1}}$, much larger than those of air, hard boundaries are assumed for the walls of resonators. Periodic boundary on both sides is chosen owing to the periodicity of the designed cells. From the result in Fig. 2(a) we can see that at the coupled resonant frequency, both resonators are excited at an out-of-phase mode. Specifically, the velocity field shows that air particles near the metasurface are vibrating parallel to the surface. Fig. 2(a) also shows that due to the resonance of the cell, the pressure amplitude inside the resonators is much larger than the incident wave pressure. Since energy absorption is proportional to the square of the pressure amplitude, such a strong vibration can efficiently dissipate the energy even with a small loss factor in the air, in which case most of energy absorption is located at the neck region.

TABLE I. Parameter of dimensions of the dark absorber. All parameters are in unit of mm.

D	H	a	b	w_1	w_2	l
58	40	20	20	2.3	3	6

Total absorption can further be explained by calculating the relative impedance of the metasurface to that of the air. Impedance of the metasurface is calculated by $Z = \langle p\rangle/\langle v_\perp\rangle$ where p is the total pressure, $v_\perp$ is velocity normal to the surface, and $\langle\cdot\rangle$ denotes averaging over the surface. Relative impedance Z_r can then be calculated by normalizing the impedance with $Z_{air} = \rho_{air}c_{air}$. Fig. 2(b) shows the real part and imaginary part of Z_r. At the frequency of absorption peak, we have $Re(Z_r) = 1$ and $Im(Z_r) = 0$, indicating impedance match of the metasurface to the background media. For above reasons, the metasurface becomes "dark" to the incident wave. We also examined, in simulation, the absorption rate for oblique incident wave by sending Gaussian modulated beam towards our metasurface at different angles. The result shows that the absorption remains higher than 95% for an incidence angle of 0° to 70°, and absorption peak frequency only shifts less than 1 Hz for incident angle less than 70°. This is because the transverse dimension of our structure is much smaller than a wavelength, making each cell close to a point sink to the incident sound.

In our experimental setup, we integrated three parallel resonators as the unit cell instead of two. Note that there is no fundamental difference between two or three resonators, and we chose three resonators design because it generates a symmetric resonant mode, which fits better with our 1D wave guide for measurements. Two parallel resonators create an anti-symmetric mode, which would require a periodic boundary. The sample is put in an impedance tube and the measurement is done with two-microphone method,[50] as shown in Fig. 3. Photo of the sample is also shown in Fig. 3. The neck widths of the two resonators are 3 mm and 4 mm, respectively. The neck length of 10 mm and the cavity dimensions of 15 mm × 20 mm are the same for both. The unit cell is fabricated with acrylonitrile butadiene styrene (ABS) plastic using fused filament fabrication (FFF) 3D printing technology. Some dust was left in the cavity to enhance absorption. As the metasurface is backed with a hard aluminum wall, sound transmission can be neglected. Therefore, we use $A = 1 - R^2$ to calculate the energy absorption, where R denotes reflection coefficient.

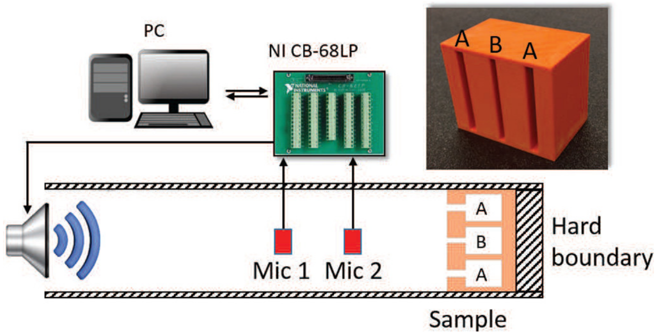

FIG. 3. Schematics of the one dimensional wave guide for measurements. Reflection coefficient and surface acoustic impedance are calculated with two-microphone method. Upper right is a photo of a fabricated sample. A and B stand for two different types of resonators.

From the results in Fig. 4, we can see that experimental result agrees well with simulation. In the figure it is clear that at "dark" frequency 1432 Hz, 98.4% of energy absorption is observed with a 50% absorption bandwidth of around 100 Hz. Note that there is a frequency shift of 9 Hz between simulation and experiment, and we attribute this to the loss caused by imperfect boundary condition and fabrication error. The shape of the experimental curves matches very well with simulation, and the plot of relative impedance shows that impedance of the metasurface matches well with the impedance of air.

This concept can be applied to create relatively broadband low frequency absorbers, as shown in Fig. 5. In the low frequency design, 3D resonators are used instead of 2D ones so that the metasurface structure remains small. Experimental results from Fig. 5 show a near-perfect absorption of >99% at 511 Hz with a 50% absorption bandwidth of around 140 Hz. Also, the impedance of the metasurface is matched to that of the air within experimental uncertainty. This absorber has a relatively broad bandwidth (27%). This is because even in the vicinity of the dark frequency where two resonators are not strongly coupled, the resonators still generate significant

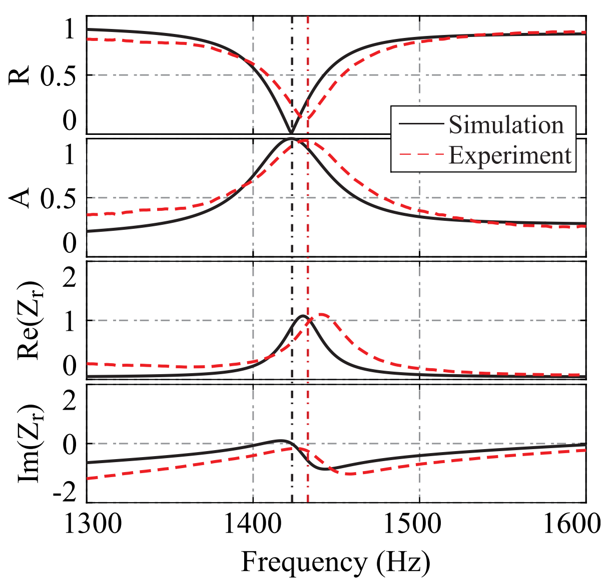

FIG. 4. Experimental results show reflection coefficient (R), absorption coefficient (A), and real part and imaginary part of relative impedance to the background media. Near-total absorption at 1432 Hz is clearly observed.

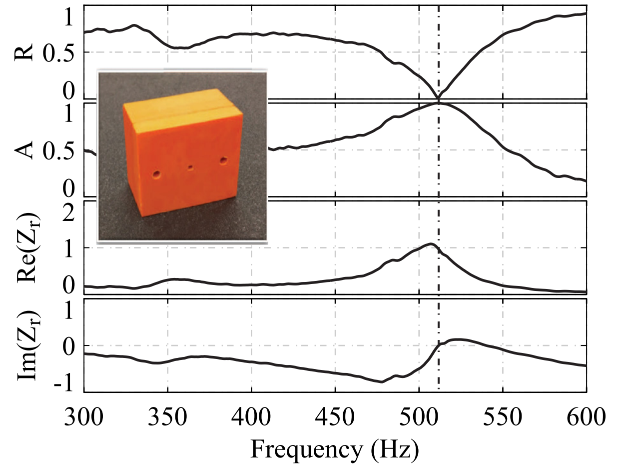

FIG. 5. Applying the idea to low frequency regime. Near-perfect absorption of over 99% is observed at 511 Hz with a 50% absorption bandwidth of about 140 Hz. Impedance of the metasurface matches the impedance of the air with a thickness of $\lambda/20$.

response at their own resonant frequencies, respectively, behaving as discrete resonating absorbers, and thus the energy is dissipated effectively within a relatively broad band.

Since the "dark" mode is created by coupling the resonance of the resonators, dark frequency is mainly determined by two factors: one is resonant frequency of the individual resonators, and the other is radiation impedance caused by strong coupling of the resonators. If loss of the resonators is reduced, difference between resonators should be reduced to keep the coupling strong enough. Coupling between resonators also become less coupled when they are separated further apart. In order to lower the resonant frequency, we may further increase the cavity size or neck length of the resonator, or add other elements to the resonator, such as a membrane. Low frequency perfect absorption may also be achieved by using other types of resonances, such as Fabry–Perot resonance by coiling up the space, or Mie resonance as suggested in Ref. 31. In order to change the coupling of the resonators, we can adjust the distance between the openings, or use different arrangements of the resonators. For the purpose of broadening the bandwidth, some amount of loss can be added to the resonators by adding some sound absorbing materials in the cavities, and separate two resonant frequencies further apart at the same time to make sure two resonators still have an out-of-phase response. For example, by making the difference between the two neck widths larger. Broader bandwidth may also be achieved by combining different cells targeted at different frequencies.[24]

To conclude, we have proposed and experimentally demonstrated a method for the design of subwavelength perfect sound absorbers. By coupling multiple resonators based on rigid structures, we designed and fabricated a metasurface that converts the incident wave to an impedance matched non-radiating surface mode, thereby absorbing the incident energy and rendering it dark to the incident sound. Over 99% energy absorption is achieved in the experiment. The proposed design yields near perfect absorption experimentally with subwavelength dimensions ($\lambda/20$). When compared with membrane type acoustic metamaterial, the proposed metasurface has a broader bandwidth, is simple to fabricate, and is structurally rigid and thus stable for long periods. Such absorbers can also, in principle, be applied to other audible frequency regime, ultrasonic regime, and water-based acoustics, and can serve as a promising approach for acoustic absorption in fields of noise control, acoustic energy harvesting, acoustic filtering, ultrasound imaging, drug delivery, and topological acoustics.

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