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HIGH-EFFICIENCY SOUND ABSORBER WITH HYBRID METAMATERIAL STRUCTURE AT LOW FREQUENCY

A new hybrid metamaterial (HMM) comprises a circular split ring of tungsten covered by a circular split ring of silicon carbide in a layer of polydimethylsiloxane (PDMS) polymer, epoxy, steel, rubber, fiberglass, or carbon fiber, respectively, to develop a low-frequency sound absorber. We carried out finite element simulations with COMSOL Multiphysics software to take theoretical measurements for acoustic hybrid metamaterial and demonstrate the influence of structural parameters. The results demonstrate that material type, geometric characteristics, and change in diameter for circular split rings of tungsten with visco-thermal losses can control the dissipative loss effect. This enables the construction of highly efficient absorber (99%) at low frequencies across a broad low-frequency spectrum. The present study paves the way for a novel approach to advancing the design of acoustic hybrid metamaterial and controlling underwater acoustic waves.

Keywords: acoustic metamaterial, hybrid metamaterial, sound absorption coefficient, underwater acoustic waves, noise attenuation.

1. Introduction

In the past few decades, acoustic metamaterials [1–4] and metasurfaces [5–7] have emerged as alternative solutions to conventional materials' problems. Previous research has employed artificial acoustic structures, such as Helmholtz resonators, [8–10] Fabry–Perot resonators [11, 12] split-tube resonators, coherent perfect absorbers, and metasurface-based absorbers [13], to build high-performance sound absorbers in the low-frequency region [14]. Acoustic metamaterials have expanded in importance in recent years because of their superior broadband sound absorption abilities [15]. One of the unique characteristics of acoustic metamaterials is their ability to absorb low-frequency sound waves on a subwavelength scale optimally. Using space-coiling arrangements [16–19] embedded necks [20, 21] or multi-layer structures with holes [22–24], one can use Helmholtz resonance in order to achieve optimal absorption in airborne acoustics [25]. Acoustic metasurfaces are man-made two-dimensional acoustic metamaterials that are used in many different domains, such as anomalous reflection, transmission, focusing, absorption, and cloaking [26], having a thickness less than the wavelength [27]. One of the most essential aspects of underwater applications, such as acoustic stealth [28], is the ability to absorb sound underwater. Furthermore, researchers have developed a variety of additional materials and structures to absorb sound underwater. These include porous foam materials. [29–32] and locally resonant acoustic materials [33–39]. At both medium and high frequencies, these materials have demonstrate superior results with respect to sound absorption [40–45]. In recent years, acoustic metamaterials have discovered many great techniques for manipulating sound waves at subwavelength scales [46–54], and a variety of innovative underwater sound-absorbing materials have been produced. Researchers have conducted numer-

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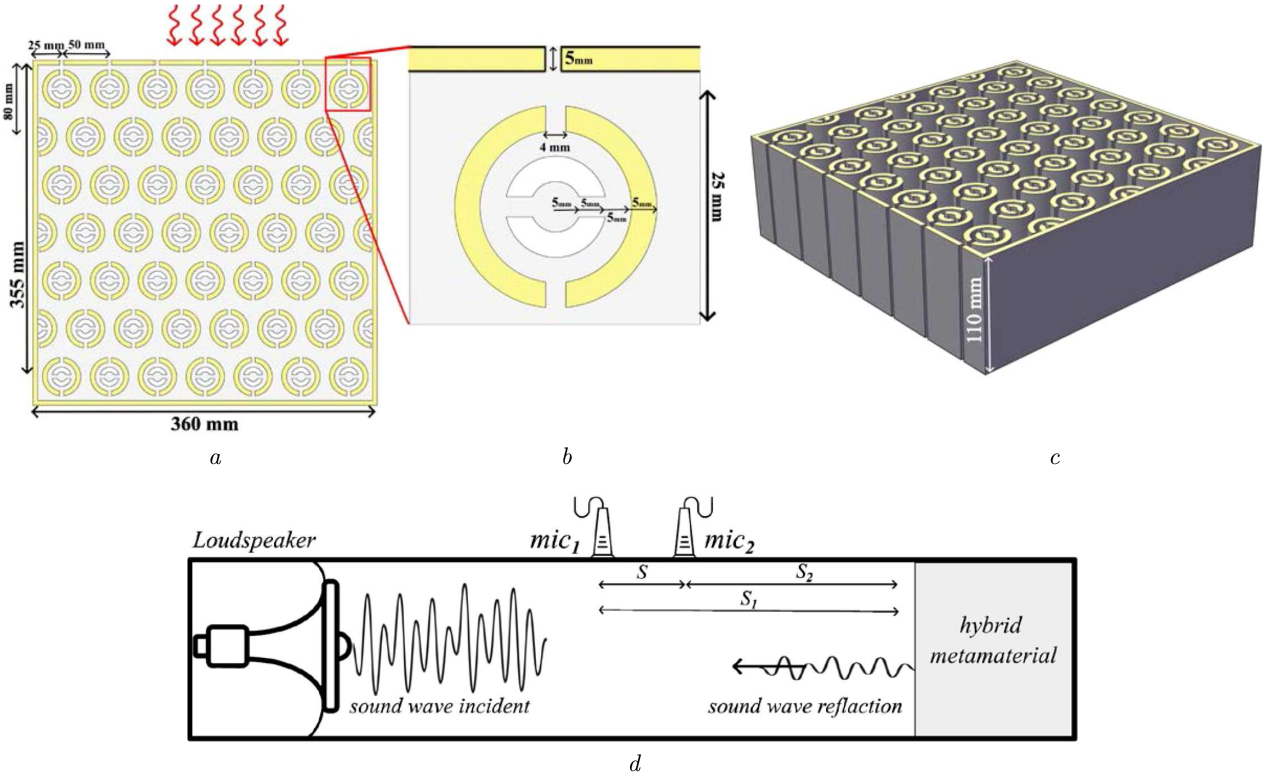
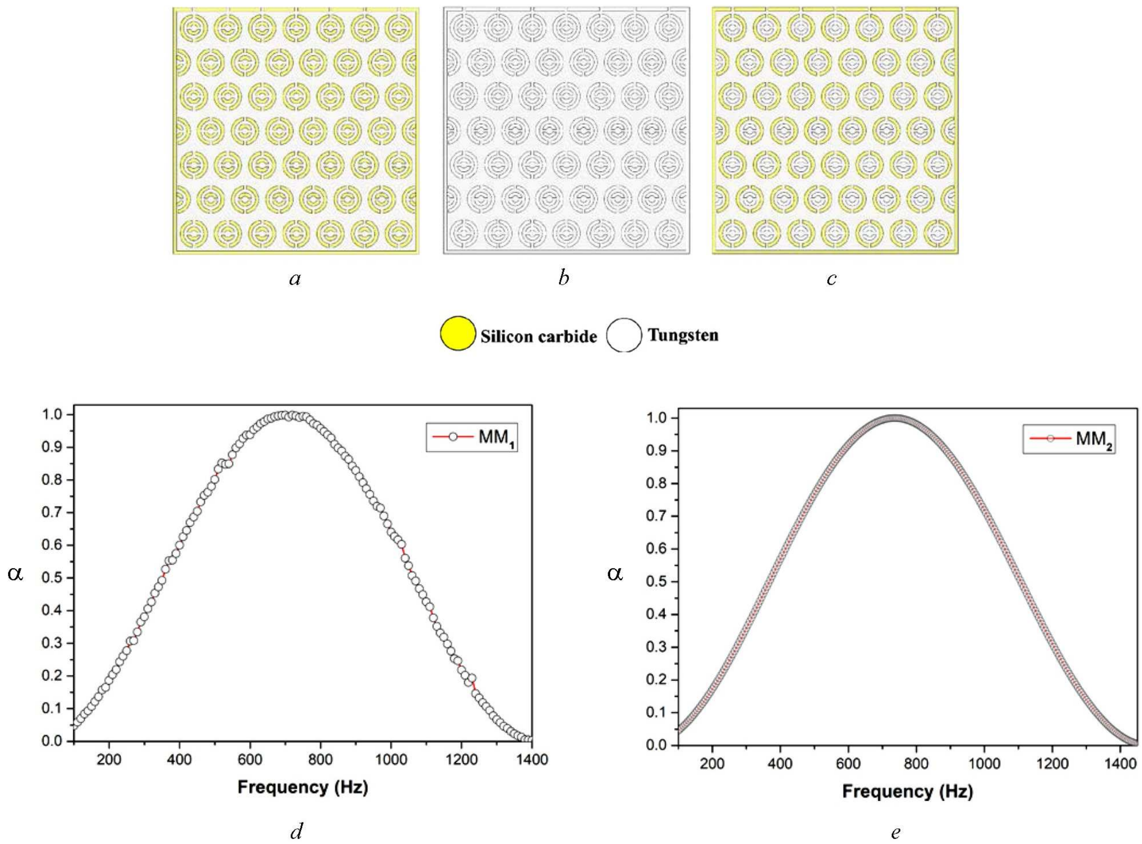


Fig. 1. The simulation model represents the design of a hybrid metamaterial structure periodically arranged (*a*), a schematic diagram of the hybrid metamaterial (HMM) unit (*b*), a schematic diagram of the hybrid metamaterial structure (3D) with height (110 mm) (*c*). The HMM were placed in Aluminum tube with a square cross-section, two microphones in the one-port technique (*d*)

ous studies on the integration of various resonance effects in the design of underwater sound absorption structures. These studies only used one type of resonance structure, such as holes or locally resonant structures. To achieve perfect low-frequency underwater sound absorption, Zhou *et al.* indicate a hybrid metamaterial consisting of a perforated panel, a water chamber, and a coiled water channel coupled with a rubber coating on the channel wall [55]. Chen *et al.* [56–58] conducted a recent study that examined dissipative elastic metamaterials in the field of broadband wave mitigation. The researchers explored the wave attenuation mechanism, explicitly focusing on the negative effective mass density and effective metadamping [44]. Ryoo *et al.* proposed a thin acoustic metasurface that can absorb a wide range of low-frequency noise by utilising hybrid resonant frequencies [59]. Yang *et al.* introduced a novel hybrid-mechanism metastructure that combines the resonances of locally resonant scatterers and air cavities. This metastructure's design allows for the effective absorption of waterborne sound across a broad range of frequencies [44]. Zhou *et al.* propose a hybrid metamaterial, a new type of underwater absorber consisting of carefully designed units arranged periodically [45]. This paper will investigate the acoustic metamaterial using finite element simulations carried out on the commercial multiphysics software COMSOL interaction of hybrid metamaterial structure (HMM), which is used in studying the design of a perfect sound absorber using HMM. First, the hybrid metamaterial absorber comprises two circular split rings immersed in water. Second, the ideal absorption performance of the acoustic hybrid metamaterial is composed of a circular split ring of tungsten that is covered by a circular split ring of silicon carbide enclosed by a layer of materials represented by polydimethylsiloxane (PDMS) polymer, epoxy, steel, rubber, fiberglass, or carbon fiber, respectively, immersed in water. Finally, this work employed the in-



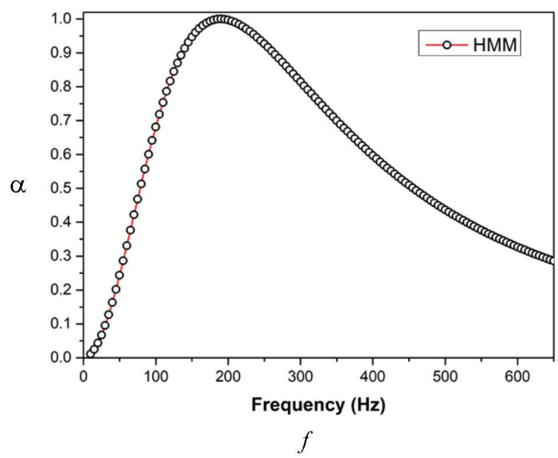


Fig. 2. Schematic diagrams of the acoustic metamaterial structure MM_1 and MM_2, respectively (*a*) and (*b*). Schematic diagram of the hybrid metamaterial structure (HMM) (*c*). Sound absorption coefficients as frequency functions at MM_1 and MM_2 (*d*) and (*e*). Sound absorption coefficient as frequency functions at HMM (*f*)

fluence of modifications for a circular split ring diameter of tungsten on hybrid metamaterial absorber performance at low frequencies.

2. Models and Methods

Figure 1, *a* demonstrates the proposed hybrid metamaterial structure (HMM) designed and periodically arranged based on the two circular split rings. Each unit cell comprises a circular split ring of tungsten covered by a circular split ring of silicon carbide enclosed by a material layer, as shown in Fig. 1, *b*, in order to achieve super-sound absorber performance.

The COMSOL Multiphysics programmer was designed to develop a theoretical model for the sound

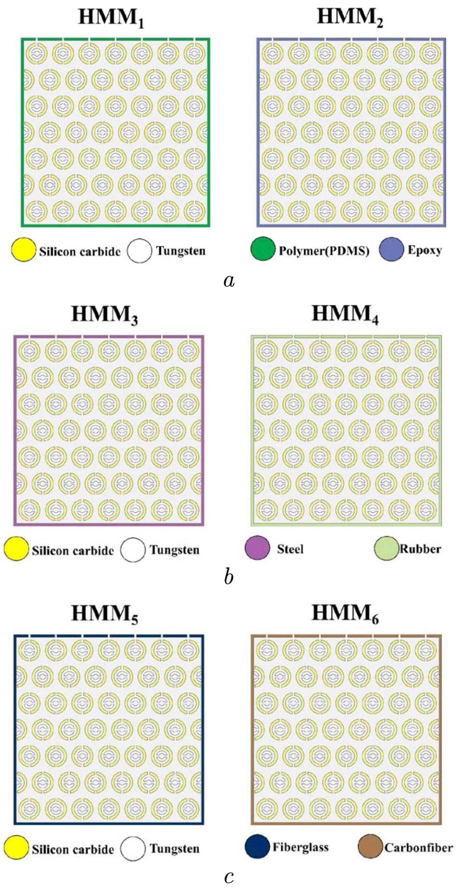


Fig. 3. A schematic diagram illustrates the models of hybrid metamaterial structures (*a*), (*b*) and (*c*)

Table 1. **Physical parameters of material used in the simulation**

Materials	Speed of sound [$m \cdot s^{-1}$]	Density [$Kg \cdot m^{-3}$]	Poisson's ratio (ν, 1)	Loss factor (η, 1)	Young's modulus (E, Pa)
Air	343	1.2	1.4	–	–
Water	1490	1000	0.5	–	–
Silicon carbide	3882	3200	0.192	–	4×10^{11}
Tungsten	5220	17800	0.29	–	3.4×10^{9}
Polymer (PDMS)	1000	995	0.5	0.1	2.8×10^{9}
Epoxy	2540	1180	0.3	0.6	1.4×10^{8}
Steel	5825	7780	0.33	–	2×10^{11}
Rubber	60	1300	0.495	0.3	10^{4}
Fiberglass	2740	2000	0.23	0.05	5.2×10^{8}
Carbon fiber	11392	1750	0.28	–	2×10^{11}

absorption of the acoustic hybrid metamaterial as $\alpha = 1 - |R|^2$, with R representing the reflection coefficient. The complex sound pressures at the measurement positions are then [60]

$$p_1 = p_i\, e^{iks_1} + p_r e^{-iks_1}, \tag{1}$$

$$p_2 = p_i e^{iks_2} + p_r e^{-iks_2}. \tag{2}$$

The two complex sound pressures can then be obtained from the measurements as

$$p_i = (p_1 e^{iks} - p_2) e^{-iks_1}, \tag{3}$$

$$p_r = (p_2 - p_1 e^{-iks}) e^{iks_1}, \tag{4}$$

where p_r and p_i are reflected and incident plane modes, respectively. The transfer function between the complex pressures obtained at two distinct microphone locations

$$H_{12} = (((p_1 e^{iks} - p_2) e^{-iks_1}) e^{iks_2} + \\ + ((p_2 - p_1 e^{-iks}) e^{iks_1}) e^{-iks_2}) / (((p_1 e^{iks} - p_2) e^{-iks_1}) \times \\ \times e^{iks_1} + ((p_2 - p_1 e^{-iks}) e^{iks_1}) e^{-iks}), \tag{5}$$

where s is the microphone spacing, s_1 is the distance between the acoustic metamaterial and the first microphone location,s_2 is the distance between the acoustic metamaterial and the second microphone location, and k represents the wave number, as shown in Fig. 1, *d*. The following describes the transfer function of incident and reflection sound waves at the two microphone locations

$$H_i = e^{iks_1}, \tag{6}$$

$$H_r = e^{-iks_1}. \tag{7}$$

The reflection coefficient of the acoustic metamaterial is obtained as follows [61]

$$R = \frac{H_{12} - H_i}{H_r - H_{12}}\, e^{2ik(s+s_1)}. \tag{8}$$

3. Results and Discussion

3.1. Effects of the acoustic hybrid metamaterial absorber underwater

The comparison between the acoustic metamaterial structure (MM) and a hybrid metamaterial structure (HMM) is considered. The metamaterial structure (MM_1), two circular split rings from silicon carbide, as shown in Fig. 2, *a*. The metamaterial structure (MM_2), two circular split rings from tungsten, as shown in Fig. 2, *b*. The hybrid metamaterial structure (HMM), comprising a circular split ring of tungsten that is covered by a circular split ring of silicon carbide, as shown in Fig. 2, *c*. The absorption spectrum for typical incident sound ($\theta_i = 0$) was studied in the low-frequency range. At MM_1 and MM_2, it can be observed that the sound absorber ($\sim$1) is located at frequencies near 700 Hz and 735 Hz, respectively, as shown in Fig. 2, *d* and 2, *e*. Fig. 2, *f* illustrates how the hybrid metamaterial structure (HMM) performs better at absorbing sound ($\sim$1) at about 190 Hz. The simulation results reveal that the super sound absorber of HMM is superior to that of MM_1 and MM_2 via adjusting the visco-thermal effect of controlling the loss of the acoustic wave. The structured composite represents a new type of acoustic metamaterial that promises broad sound absorption applications at low-frequency.

3.2. Effects of the acoustic hybrid metamaterial absorber models

We design meta-absorbers based on the confirmed hybrid metamaterial structure in order to achieve the best performance in perfect acoustic absorption over a wide low-frequency range. We have structured composites made from new HMM models. The hybrid metamaterial structure is made of a circular split ring from tungsten covered by a circular split ring from silicon carbide, which is embedded into the materials represented by polydimethylsiloxane (PDMS) polymer, epoxy, steel, rubber, fiberglass, or carbon fiber, respectively, as shown in Fig. 3. Table 1 presents the physical parameters of the materials used.

The models of HMM that affect the acoustic absorption peak at low frequencies. Physical parameters can regulate the sound absorption performance of the HMM. In Figs. 3, *a* and 3, *b*, we focus on the effect of HMM_1 and HMM_2 on sound absorbers. Figure 4, *a* shows the peak value of α at ($\sim$1) within the frequency range of 465 Hz and 455 Hz, respectively. We also investigated the sound absorption performance of the hybrid metamaterial absorbers under different physical parameters in HMM_3 and HMM_4. The simulated perfect absorption curve in Fig. 4, *b* is visible at approximately 300 Hz and 280 Hz frequencies, respectively. Figure 4, *c* shows the influence of the materials (fiberglass and carbon fiber) of HMM_5 and HMM_6, respectively, on the sound absorption performance of the hybrid metamaterial absorber. The acoustic absorption is achieved at ($\sim$1) with the values of the frequencies at 255 Hz and 245 Hz, respectively. The simulation results reveal

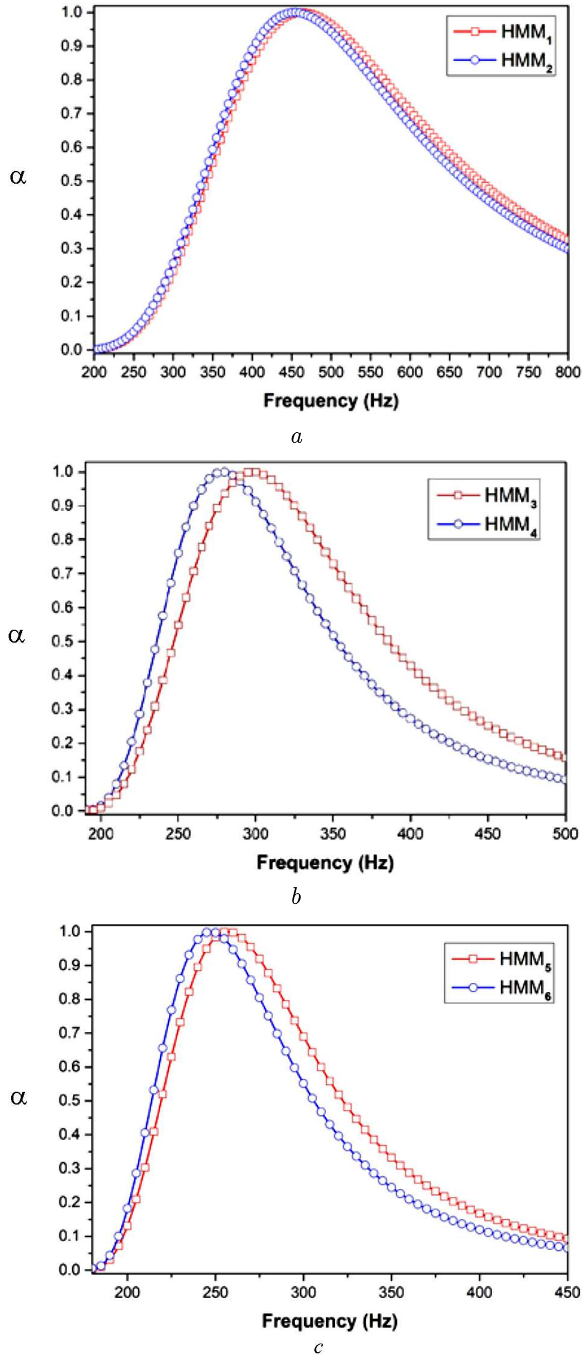


Fig. 4. Sound absorption coefficients as frequency functions for hybrid metamaterial structures (*a*), (*b*) and (*c*)

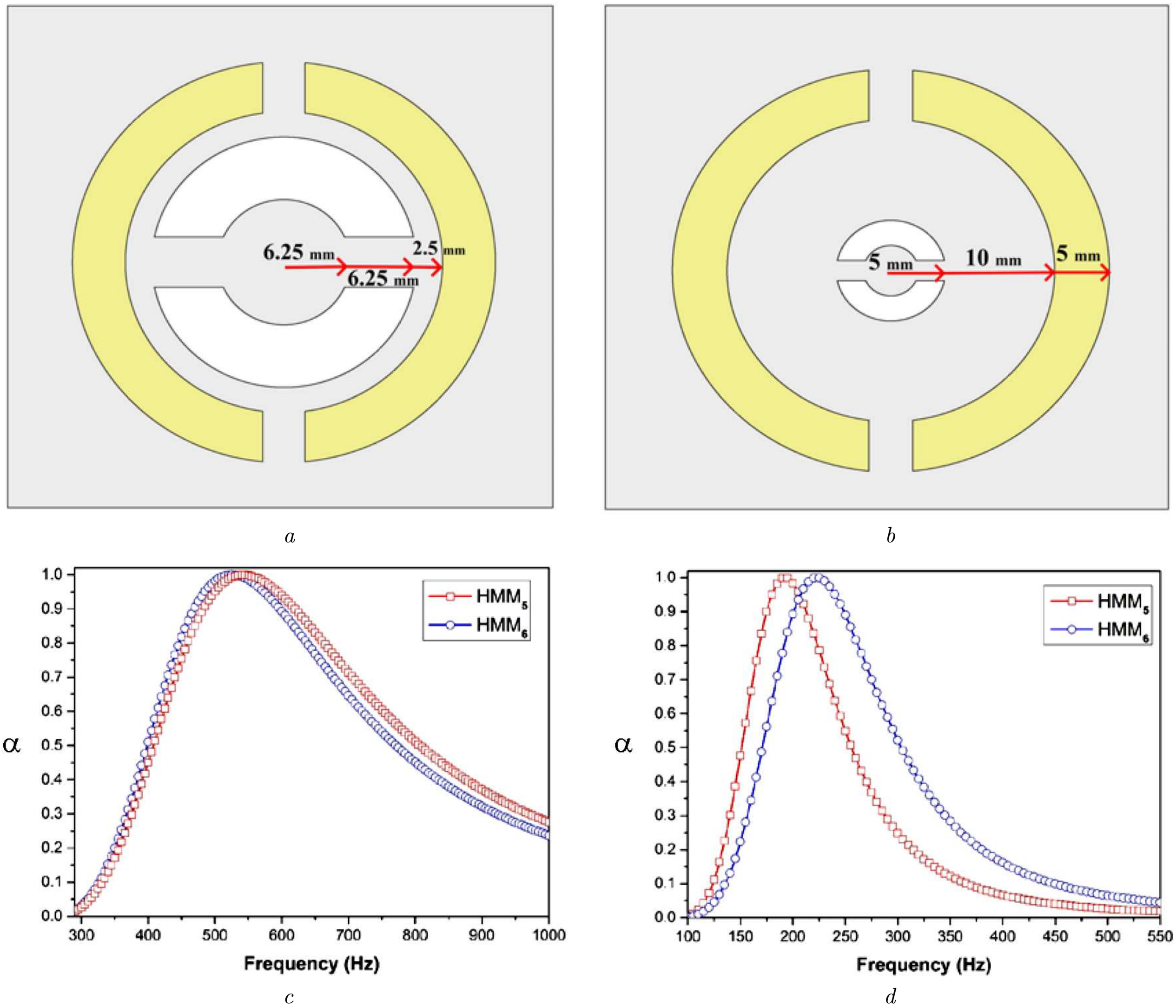


Fig. 5. The schematic diagram of the hybrid metamaterial structure (HMM_5 and HMM_6) for a diameter 5 mm (*a*). The schematic diagram of the hybrid metamaterial structure (HMM_5 and HMM_6) for a diameter 12.5 mm (*b*). (c) The sound absorption as frequency functions for a diameter 5 mm at HMM_5 and HMM_6, respectively (*c*). The sound absorption as frequency functions for a diameter 12.5 mm at HMM_5 and HMM_6, respectively (*d*)

the efficient acoustic hybrid metamaterial absorber underwater. These results indicate that the newly designed hybrid metamaterial structure has perfect acoustic absorber properties and will be promising in reducing noise. The structural and material parameters of the proposed hybrid metamaterial closely influence its acoustic absorber. The HMM_5 and HMM_6 can achieve superior sound absorption at 255 Hz and 245 Hz, respectively. It combines the low-frequency performance of the physics material parameters with the energy dissipation effect. The novelty-designed HMM_5 and HMM_6 have highly efficient sound absorption properties and will be helpful in engineering applications.

Our study of the impact of modifying the circular split ring diameter for tungsten at the HMM_5 and HMM_6 structures has the potential to enhance sound absorption significantly. The HMM_5 and HMM_6 have 5 mm and 12.5 mm diameters, respectively, as shown in Figs. 5, *a* and 5, *b*. At frequencies of 545 Hz and

525 Hz, we show unitary sound absorption at a diameter of (5 mm) in HMM_5 and HMM_6, respectively, as shown in Fig. 5, *c*. In Fig. 5, *d*, we show that the perfect sound absorption peak in HMM_5 and HMM_6 is around 190 Hz and 225 Hz at diameter (12.5 mm), respectively. It was observed that viscous damping and friction loss achieve superior acoustic absorption. These results show that a 12.5 mm diameter is a high-efficiency sound absorber and achieves new possibilities in underwater acoustic applications.

4. Conclusion

In summary, we constructed a hybrid metamaterial structure (HMM) to satisfy the highly efficient acoustic absorber at low frequencies immersed in water by creating a circular split ring from tungsten covered by a circular split ring of silicon carbide embedded into the materials. The ability of two circular split rings enclosed by a layer of polydimethylsiloxane (PDMS) polymer, epoxy, steel, rubber, fiberglass, or carbon fiber, respectively, to enhance acoustic absorption. The theory of the sound absorber of hybrid metamaterial is proposed. Our investigation focused on the concept of an HMM absorber with changes in the physical parameters of the material and the diameter of circular split rings for tungsten. This feature was exploited for sound absorbers by adjusting the periodic arrangement of metamaterial structure and the physical parameters. This resulted in enhanced dissipation acoustic wave energy capabilities due to friction. The hybrid metamaterial designed for highly efficient absorption demonstrates significant potential, achieving near to ($\alpha \sim 1$) absorption at frequencies below 300 Hz. The HMM_5 and HMM_6 are considered structures with a high absorption capacity for sound waves at low frequencies for 12.5 mm diameter of the inner rings. This paper is significant for the development of acoustic hybrid metamaterial and the manipulation of underwater acoustic waves.

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ВИСОКОЕФЕКТИВНЕ ПОГЛИНАННЯ ЗВУКУ НИЗЬКОЇ ЧАСТОТИ СТРУКТУРОЮ З ГІБРИДНИМ МЕТАМАТЕРІАЛОМ

Ми виготовили та дослідили новий поглинач звуку низької частоти з нового гібридного метаматеріалу, який складається з круглого розрізного кільця з вольфраму, покритого круглим розрізним кільцем карбіду кремнію в шарі полімеру полідиметилсилоксану (PDMS), епоксидної смоли, сталі, гуми, скловолокна або вуглецевого волокна, відповідно. Ми провели моделювання методом скінченних елементів за допомогою програмного забезпечення COMSOL Multiphysics. Результати показують, що запропонований підхід дозволяє створювати високоефективний поглинач (99%) у широкому діапазоні низькочастотного спектра. Дане дослідження прокладає шлях до вдосконалення проектування акустичного гібридного метаматеріалу та контролю, зокрема, підводних акустичних хвиль.

Ключові слова: акустичний метаматеріал, гібридний метаматеріал, коефіцієнт поглинання звуку, акустичні підводні хвилі, затухання шуму.