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(54) Title: DEGENERATE RESONATORS USING ELASTIC METAMATERIALS WITH INDEPENDENT MONOPOLE AND DIPOLE RESONANT STRUCTURES

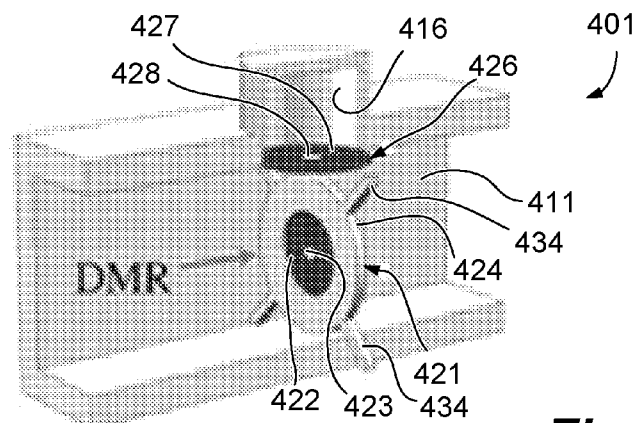


Fig. 4A

(57) Abstract: A sound absorbing metamaterial is provided with an acoustic impedance-matched surface, which is configured to minimize reflection and transmission of an incident acoustic wave. The surface has a dipole sub-unit (101) and a monopolar sub-unit (102). The dipole sub-unit (101) has a decorated membrane resonator (DMR) with an elastic membrane (123) for the dipole mounted on a fixed frame (124) and a platelet (125) attached to the membrane (123). The monopolar sub-unit (102) has at least two decorated membrane resonators as the two sides of the monopolar sub-unit (102), or a DMR backed by a sealed air cavity mounted on the side wall, and is responsive to vibration or sound by displacement on the two sides equal in amplitude but opposite in direction.



Degenerate Resonators using Elastic Metamaterials with Independent Monopole and Dipole Resonant Structures

BACKGROUND

[0001] Field

[0002] This disclosure relates to acoustic metamaterial that relates to acoustic energy absorption using hybrid resonant metastructures.

[0003] Background

[0004] Acoustic metamaterials are manufactured or synthetic structures that have resonant transmission, absorption and reflection characteristics. Acoustic metamaterials aim to achieve acoustic and/or elastic properties which are not available from traditional materials. In particular, negativity in effective dynamic mass density was demonstrated in various designs. Materials with negative acoustic properties present a negative mass density and bulk modulus, and therefore a negative index of refraction. Negative effective bulk modulus was also realized in fluid channels with cavity resonators. Other effects such as focusing, image magnifying, acoustic cloaking, and total absorption were also realized experimentally.

[0005] Acoustic metamaterials are used to fabricate sound attenuation panels, for example, as described in U.S. Patent No. 7,395,898. U.S. Patent No. 7,395,898 discloses a rigid frame divided into a plurality of individual cells, a sheet of a flexible material, and a plurality of weights. Each weight is fixed to the sheet of flexible material such that each cell is provided with a respective weight and the frequency of sound attenuated can be controlled by suitable selecting the mass of the weight. The flexible material may be any suitably soft material such as an elastomeric material like rubber, or soft material such as nylon or other plastics. The rigid frame may be made of a material such as aluminum or plastic.

[0006] Total absorption of sound using subwavelength structures or materials has always been a challenge, since the linear dynamics of dissipative systems dictates the dissipation power to be linearly proportional to the elastic deformation energy, which is negligible in the sub-wavelength scale. To enhance dissipation, it is usually

necessary to increase the energy density, for example, through resonances. In an open system, radiation coupling to resonances is an alternative that can be effective in enhancing dissipation. In previous studies, by utilizing localized subwavelength resonances, membrane-type metamaterial, containing a Decorated Membrane Resonator (DMR) with tunable weights, has shown efficient and flexible capability in low frequency sound absorption. A balance between dissipation and scattering at resonance has been found for optimum absorption. More recently, a perfect absorber has been realized by hybridizing DMR's two resonances through coupling via a thin gas layer. Through interference, waves reflected from such DMR have been shown to completely cancel that from a reflective wall placed a short distance (about $1/133$ of the relevant airborne sound wavelength) behind the DMR. Meanwhile, the coherent perfect absorber (CPA) in optics shows that the scattering waves at resonance can be cancelled when another counter-propagating coherent light wave (control wave), with specific phase and intensity, interferes with the incident beam, thereby leading to total absorption. Recent efforts have also been made for its analogy in acoustics. Except for some theoretical attempts in acoustic and numerical studies in optics, up to now no perfect absorber has been experimentally realized that intrinsically eliminates all the scattered waves, thereby realizing total absorption regardless of the incident direction, and with no need for a control wave.

SUMMARY

[0007] A sound absorbing metamaterial comprises an acoustic impedance-matched surface configured to minimize reflection and transmission of an incident acoustic wave. The surface comprises a dipole sub-unit and a monopolar sub-unit. The dipole sub unit comprises a decorated membrane resonator (DMR) with an elastic membrane for the dipole mounted on a fixed frame and a platelet attached to the membrane. The monopolar sub unit comprises at least two decorated membrane resonators as the two sides of the monopolar sub unit, or a DMR backed by a sealed air cavity mounted on the side wall, responsive to vibration or sound by displacement on the two sides equal in amplitude but opposite in direction.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Figs. 1A-C depict dipole and monopole sub-units. Fig. 1A is a schematic side view of a dipole sub-unit. Fig. 1B is a schematic side view of a monopole sub-unit. Fig. 1C is a photographic depiction of the sub-units of Figs. 1A and 1B mounted on a solid plate in a side-by-side arrangement to form a combined unit.

[0009] Figs. 2A and 2B graphically depict the acoustic spectra of the sub-units of Figs. 1A-C. The curve starting on the lower left (solid or black curve) of Fig. 2A depicts the transmission spectrum of the dipole sub-unit. The curves starting on the upper left are for the monopole sub-unit and the combination of the dipole sub-unit and the monopole sub-unit. The curve for the monopole sub-unit (dotted or dark blue curve) has the deeper dips than the combination of the dipole sub-unit and the monopole sub-unit (dot-dashed or dark red curve). The curve in Fig. 2B depicts the absorption spectrum of the combination of the dipole sub-unit and the monopole sub-unit.

[0010] Figs. 3A and 3B graphically depict Green's functions for the sub-units of Figs. 1A-C. The solid or dark blue lines depict modulus type Green's functions and the open dots depict mass type Green's functions. Fig. 3A depicts the Green's functions over a wide range from 200 Hz to 1500 Hz. Fig. 3B depicts an enlarged region between 420 Hz and 460 Hz, where the two Green's functions are nearly equal.

[0011] Figs. 4A and 4B depict a side wall structure in a schematic diagram (Fig. 4A) and its acoustic spectra (Fig. 4B). The solid curve is the absorption spectrum. The dashed curve is the transmission spectrum. The dot-dashed line curve is the reflection spectrum.

[0012] Fig. 5 is a schematic depiction of a unit cell for 2-D lattices.

[0013] Fig. 6 is a schematic depiction of a unit cell for 3-D lattices.

DETAILED DESCRIPTION

[0014] Overview

[0015] Experimental realization of perfect sound absorption by sub-wavelength monopole and dipole resonators shows that a configuration with these resonators

exhibits degenerate resonant frequencies. This is achieved through the destructive interference of the two resonators' transmission responses, while the matching of their averaged impedances to that of air implies no backscattering, thereby leading to total absorption.

[0016] The present disclosure provides metamaterials with multiple sub-units, having different physical characteristics. The main component has a physical size at least 10 times smaller than the working sound wavelength in the medium it is embedded. At least one sub-unit possesses dipole vibration eigenmodes and another sub-unit possesses monopole vibration eigenmodes. The two sub-units are physically independent of one another. The physical independence provides a structure whereby a change of the structure of one sub-unit does not change the vibrational properties of the other. By selecting the eigenfrequencies of the two sub-units, the combined unit can serve as the unit cell for doubly negative medium; i.e., negative mass density and negative modulus. This doubly negative medium occurs when a large number of the cells are arranged in 1-dimensional, 2-dimensional, or 3-dimensional lattices.

[0017] Also by selecting the vibration eigenmodes, the combined unit can serve as a super absorption device; i.e., its perfect elastic wave absorption area is significantly larger than its physical size.

[0018] Two non-limiting examples are described herein, both using decorated membrane resonators (DMRs) as the basic units. The first example uses a flat panel comprising a DMR and a pair of coupled DMRs, while the second one uses a ventilated short tube containing a DMR in conjunction with a sidewall DMR backed by a cavity. In both examples, near perfect absorption, up to 99.7% has been observed with the airborne wavelength up to 1.2 m, which is at least an order of magnitude larger than the composite absorber.

[0019] The present disclosure provides a total acoustic absorption unit comprising a monopole (symmetric under mirror reflection) and a dipole (anti-symmetric under mirror reflection) resonator that are resonant at the same frequency, as a degenerate absorption unit. Similar to hybrid resonance, this degenerate absorption unit can have two useful degrees of freedom, inherited from the two resonances. During a scattering event, reflection can be eliminated by making the average impedance of the

two resonators to be impedance-matched with the background medium. Transmission can also be eliminated if the response on the other side is zero due to destructive interference. The net result is a perfect absorber that scatters no sound and that does not need a reflecting back wall as in the hybrid membrane resonator (HMR) or another controlling wave as in the CPA. Owing to its subwavelength dimensions, acoustic waves incident from any direction will be completely dissipated.

[0020] In the flat panel composite absorber, a DMR dipolar resonator was built on the same panel with a pair of DMRs that are coupled by a thin layer of sealed air, which can generate a monopole resonance as well as a dipole resonance. When the coupled-DMR's monopolar resonance has the same resonance frequency as the DMR, absorption approaching perfect absorption of sounds is observed in both numerical simulations and experiments.

[0021] **Configuration**

[0022] Figs. 1A-C depict dipole and monopole sub-units. Fig. 1A is a schematic side view of a dipole sub-unit 101. Fig. 1B is a schematic side view of a monopole sub-unit 102. Fig. 1C is a photographic depiction of the sub-units 101, 102 of Figs. 1A and 1B mounted on a rigid supporting structure 105 in a side-by-side arrangement to form a combined unit.

[0023] Referring to Fig. 1A, the dipole sub-unit 101 is a decorated membrane resonator (DMR) with an elastic membrane 123 mounted on a fixed frame 124 and a platelet 125 attached to the center of the membrane 123. As the name implies, the dipole sub-unit 101 possesses dipole eigenmodes.

[0024] The monopole sub-unit 102 comprises a cavity 131 with its two surfaces 141, 142 each made of a DMR. Fixed frame 144 is used to mount the two surfaces 141, 142 and form the cavity 131. The cavity 131 is then mounted on a larger membrane 146 fixed on a larger frame 149. As the name implies, the monopolar sub-unit 102 possesses monopolar eigenmodes.

[0025] The monopolar and dipolar resonances can be distinguished from their motions on two sides. For monopole 102, depicted in Fig. 1B, the displacement on the two sides should be equal in amplitude but opposite in direction; whereas for

dipole 101 depicted in Fig. 1A, the two-side displacements at resonance have the same amplitude and direction.

[0026] The two sub-units 101, 102 are then mounted on a rigid supporting structure 105, such as the hard plastic plate as shown in Fig. 1C, to form a combined unit. Fixed frames 124 and 149 are mounted to the rigid supporting structure 105, whereas fixed frame 144 floats on membrane 146.

[0027] The transmission spectra when the two sub-units 101, 102 were measured separately and when the two sub-units 101, 102 were placed in parallel are shown in Fig. 2A. For the dipole sub-unit 101, the first dipole resonance is at 443 Hz, the second dipole resonance is near 800 Hz, and the third dipole resonance is above 1600 Hz. The first and the second dipole anti-resonances are near 500 Hz and 1500 Hz, respectively. For the monopole sub-unit 102, the first dipole resonance is at 93 Hz, while the second dipole resonance is near 300 Hz. The first dipole anti-resonance is near 200 Hz. The third dipole resonance is at 800 Hz, and the second dipole anti-resonance is around 550 Hz. Its first monopole resonance is deliberately tuned to 443 Hz, which is almost the same as that of the first dipole resonance of the dipole sub-unit 101. Its second monopole resonance is around 1230 Hz. The first monopole anti-resonance is around 1000 Hz. Unlike the dipole anti-resonances, the transmission dip of the monopole anti-resonance is not as pronounced as the dipole anti-resonances, because of the large imaginary part of the Green's functions.

[0028] Figs. 2A and 2B graphically depict the acoustic spectra of the sub-units 101, 102 and the combined unit of Figs. 1A-C. The curve in Fig. 2A starting on the lower left (solid line) depicts the transmission spectrum of the dipole sub-unit 101. The graph depicts spectra between 50 Hz and 1500 Hz. The curves starting on the upper left are for the monopole sub-unit 102 (dotted dark blue line) and the combination of the dipole sub-unit 101 and the monopole sub-unit 102 (dot-dashed dark red line). The curve for the monopole sub-unit 102 (dotted dark blue line) has the deeper dips than the combination of the dipole sub-unit 101 and the monopole sub-unit 102 (dot-dashed dark red line).

[0029] Fig. 2B shows near unity super absorption at 443 Hz of the combined unit. The cross section area of the waveguide is about three times the physical area of the combined unit.

[0030] The relevant Green's functions of the combined unit extracted from the experimental transmission and reflection spectra are shown in Figs. 3A and 3B. Figs. 3A and 3B graphically depict Green's functions for the sub-units 101, 102 of Figs. 1A-C. The black lines depict modulus type Green's functions and the grey circles depict mass type Green's functions. Fig. 3A depicts the Green's functions over a wide range from 200 Hz to 1600 Hz. Fig. 3B depicts an enlarged region between 420 Hz and 450 Hz, where the two Green's functions are nearly equal.

[0031] The impedance of each sub-unit can then be derived from the Green's functions. The design parameters (membrane sizes and central weights) are so chosen that the first dipole resonance frequency of the dipole sub-unit 101 around 443 Hz coincides with the first monopole resonance frequency of the monopole sub-unit 102, so that the combined unit exhibits super absorption at the overlapped resonant frequency. When two resonators are arranged side by side on a panel, their total impedance for normal incident sound is given by $1/Z_{\text{tot}} = 1/Z_1 + 1/Z_2$, where Z_1 and Z_2 are the impedances of the two sub-units 101, 102, respectively. Therefore, a perfect absorber exists if both the monopolar and dipolar resonators have the same impedance of $2Z_0$ with Z_0 being the air impedance. On the incident side, the effective impedance of the device is just the impedance of air Z_0 . The device therefore exhibits a perfectly impedance-matched surface on the incidence side, so there are no reflection waves. On the transmission side of the device, although the two resonators are strongly vibrating, their displacements are of the same amplitude while exactly opposite in phase. As long as the whole structure is sub-wavelength, the excited motions from the two sub-units 101, 102 will cancel each other in the far-field, so there are no transmission waves either. Consequently, all the incident energy is confined in the two sub-units 101, 102, and eventually dissipated by the membranes.

[0032] Figs. 3A and 3B depict the modulus type Green's functions G_λ (solid or dark blue line) and mass type Green's function G_ρ (open dots) of the combined unit in the entire frequency range (A), and in the enlarged region where the two Green's functions are nearly equal (B).

[0033] The combined unit is also a doubly negative structure in the frequency ranges where $G_\lambda < 0$ while $G_\rho > 0$. In this particular case shown in Fig. 3A, the double negativity occurs between the second dipole anti-resonance frequency (540 Hz) and the third dipole resonance (780 Hz). Changing the design parameters can tune this frequency region over a large range.

[0034] The ability to change the Green's functions of the two sub-units 101, 102 independently also allows one to make the two type of Green's functions G_λ and G_ρ of the combined unit to be nearly equal over a large frequency range, thus realizing low transmission over a wide frequency range, which breaks the myth that structures based on local resonances would inherently have only narrow band working frequencies.

[0035] Figs. 4A and 4B depict a side wall structure in a schematic diagram (Fig. 4A) and graphically (Fig. 4B), which is a ventilated composite absorber 401. In the ventilated composite absorber, a sub-wavelength short tube 411 has hybrid membrane resonator (HMR) 416 attached on the sidewall. Short tube 411, by way of non-limiting example is formed as a 35 mm deep, 55 mm wide, cylindrical chamber. In this example, short tube 411 has a dipole resonator 421, having membrane 422 with a 38 mg attached weight 423 supported by rigid rim 424. HMR 416 is sealed by dipole resonator 426 comprising rubber membrane 427, with a 130 mg attached weight 428. HMR 415 generates a monopole response in air, along the axial direction of tube 411, through the sucking and pushing of air associated with the displacement of membrane 421.

[0036] Dipole resonator 426 is a 40 mm-wide membrane placed at the center of tube 411, with a rigid rim 424 at 8 mm in its width. Rigid rim 424 is supported by four poles 434. In this non-limiting example, dipole resonator 421, comprising membrane 422 and rim 424 block the cross-section of tube 411 at a ratio $f_d = 0.55$. While the dipole resonator 421 gives rise to narrow discrete resonances, the air in the remaining

cross-section area contributes a smooth continuum background. Fig. 4B shows the acoustic response of ventilated composite absorber 401. The combination of these two resonators in this non-limiting example exhibits almost perfect absorption, at 285.6 Hz, with both vanishing reflection and transmission. The wavelength of sound in air here is about 1.2 m, which is 22 times larger than the thickness of the absorber and 10 times larger than its width. For their opposite symmetry, the air motion is mainly trapped between the short tube 411 and HMR 416, so that almost no sound is scattered forward. There is almost no reflection either, as the reverse velocities (backward away from the resonators) in a small distance are only that of the incoming plane wave. While sound being totally absorbed, air flow is still possible in the channel (short tube 411).

[0037] Fig. 5 is a schematic depiction of a unit cell for 2-D lattices. For a 2-D lattice, the two sub-units 101, 102 can both be DMRs on the four side surfaces of a cubic structure, but with different membrane diameter and/or central weights. Both possess monopole and dipole eigenmodes. The top and bottom sides are sealed by rigid plates. The pair can be repeatedly duplicated and arranged into a side-by-side 2-D array, or simply a row to form a sound wave absorption barrier, or a 2D lattice with negative refraction index for all sound waves propagating parallel to the 2-D plane. Their frequencies, however, can be tuned independently by choosing the right membrane diameters and central weights.

[0038] Fig. 6 is a schematic depiction of a unit cell for 3-D lattices. As is the case with the 2-D lattices of Fig. 5, the unit for 3-D can be similar to its 2-D cousin but with all six faces made of DMRs of appropriate sizes and decorations. A small and unsealed air gap exists between any two cubic sub-cells. As described above with respect to the 2-D lattices, the unit cells can be repeatedly positioned to form 3D lattice with negative refraction index or to absorb sound waves in all incident directions. The frequencies of the 3-D unit cells can be tuned independently by choosing the right membrane diameters and central weights.

[0039] Conclusion

[0040] By combining a pair of degenerate monopole and dipole resonators with subwavelength dimensions, a perfect absorption of sound can be achieved. The subwavelength dimension of the absorber unit implies that the absorption functionality is independent of the incident direction.

[0041] It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated to explain the nature of the subject matter, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

CLAIMSWhat is claimed is:

1. A sound absorbing metamaterial comprising
an acoustic impedance-matched surface configured to minimize reflection
from an incident acoustic wave, the surface comprising:
a dipole sub-unit comprising a decorated membrane resonator (DMR)
with an elastic membrane for the dipole mounted on a fixed frame and a
platelet attached to the membrane;
a monopolar sub-unit comprising at least two decorated membrane
resonators as the two sides of the monopolar sub-unit responsive to vibration
or sound by displacement on the two sides equal in amplitude but opposite in
direction.
2. The sound absorbing metamaterial of claim 1, further comprising:
a rigid supporting structure, the sub-units mounted on the supporting structure;
and
the dipole sub-unit having a resonance frequency approximately the same as a
monopole resonance frequency of the monopole sub-unit.
3. The sound absorbing metamaterial of claim 1, further comprising:
an arrangement of at least two sub-units on each of a plurality of a set of four
side surfaces of a cubic structure, with different membrane diameters and/or central
weights and respective groups of at least two sub-units possessing monopole and
dipole eigenmodes; one monopole resonant frequency of one sub-unit is
approximately the same as a dipole resonant frequency of the other sub-unit;
the cubic structure having top and bottom sides sealed by rigid plates; and
the cubic structure stackable to form columns, with frequencies tunable
independently by selection of membrane diameters and central weights.
4. The sound absorbing metamaterial of claim 1, further comprising:
an arrangement of at least two sub-units on each of a plurality of side surfaces
of a cubic structure, with different membrane diameters and/or central weights and
respective groups of at least two sub-units possessing monopole and dipole

eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;

the cubic structure having top and bottom sides sealed by rigid plates; and

the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights.

5. The sound absorbing metamaterial of claim 1, further comprising:

an arrangement of at least two sub-units on each of a plurality of a set of six side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;

the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights; and

an unsealed air gap exists between at least a subset of two cubic sub-cells.

6. The sound absorbing metamaterial of claim 1, wherein the dipole sub-unit and the monopolar sub-unit possess distinct monopole and dipole eigenmodes.

7. A sound absorbing metamaterial comprising

an acoustic impedance-matched surface configured to minimize reflection from an incident acoustic wave, the surface comprising:

means comprising a dipole sub-unit comprising a first decorated membrane resonator (DMR), to provide a first resonance frequency; and

means comprising a monopolar sub-unit comprising a second decorated membrane resonator (DMR) backed by a sealed cavity, to provide a second resonance frequency.

8. The sound absorbing metamaterial of claim 7, further comprising:

means to provide a rigid supporting structure, the sub-units mounted on the supporting structure; and

the dipole sub-unit having a resonance frequency approximately the same as a monopole resonance frequency of the monopole sub-unit.

9. The sound absorbing metamaterial of claim 7, further comprising:
an arrangement of at least two sub-units on each of a plurality of a set of four side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes; one monopole resonant frequency of one sub-unit is approximately the same as a dipole resonant frequency of the other sub-unit;
the cubic structure having top and bottom sides sealed by rigid plates; and
the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights.

10. The sound absorbing metamaterial of claim 7, further comprising:
an arrangement of at least two sub-units on each of a plurality of side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;
the cubic structure having top and bottom sides sealed by rigid plates; and
the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights.

11. The sound absorbing metamaterial of claim 7, further comprising:
an arrangement of at least two sub-units on each of a plurality of a set of six side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;
the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights; and
an unsealed air gap exists between at least a subset of two cubic sub-cells.

12. The sound absorbing metamaterial of claim 7, wherein the dipole sub-unit and the monopolar sub-unit possess distinct monopole and dipole eigenmodes.

13. A sound absorbing metamaterial comprising:

an arrangement of at least two sub-units on each of a plurality of a set of four side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;

the cubic structure having top and bottom sides sealed by rigid plates; and

the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights.

14. A sound absorbing metamaterial comprising:

an arrangement of at least two sub-units on each of a plurality of side surfaces of a cubic structure, with different membrane diameters and/or central weights and respective groups of at least two sub-units possessing monopole and dipole eigenmodes, with one monopole resonant frequency of one sub-unit approximately the same as a dipole resonant frequency of the other sub-unit;

the cubic structure having top and bottom sides sealed by rigid plates; and

the cubic structure stackable to form columns, with frequencies tunable independently by selection of membrane diameters and central weights.

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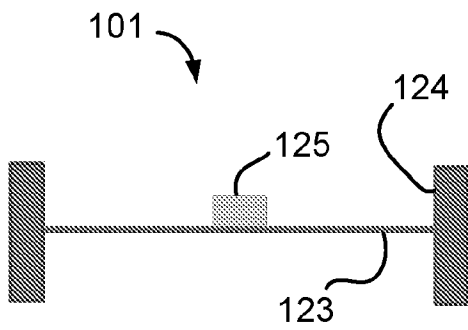


Fig. 1A

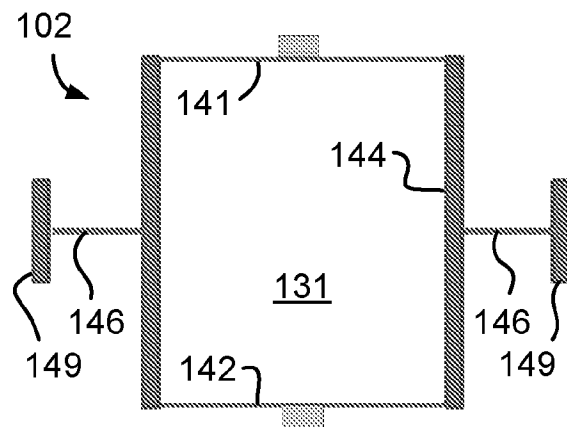


Fig. 1B

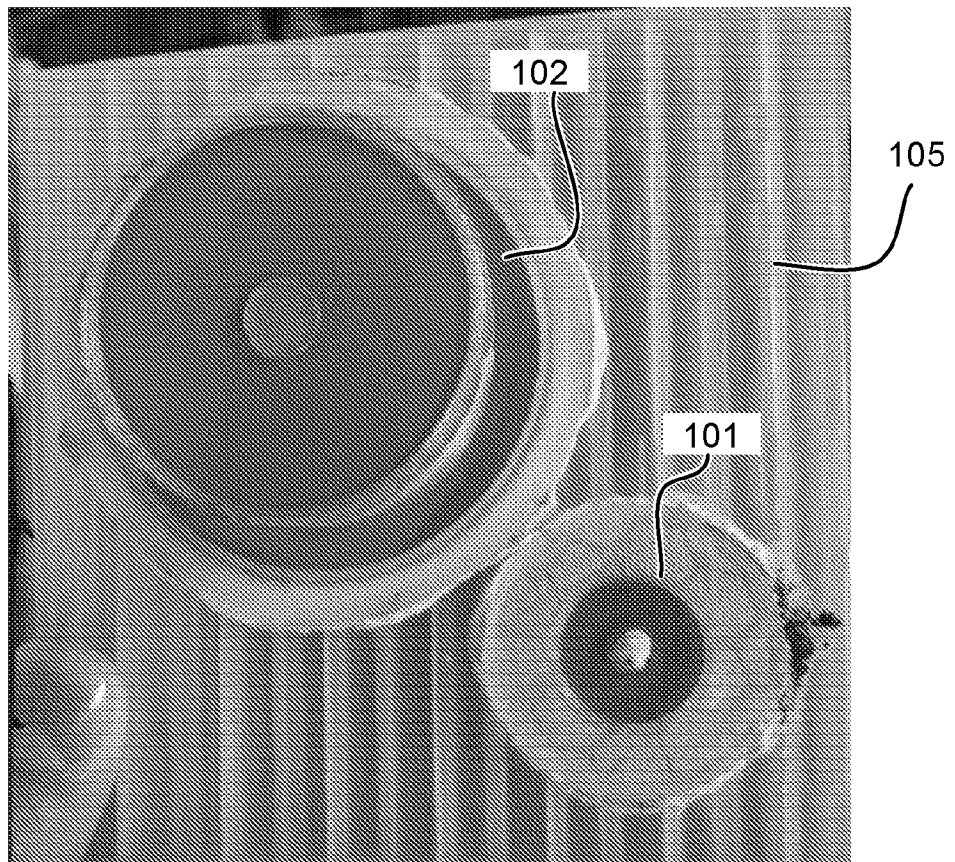
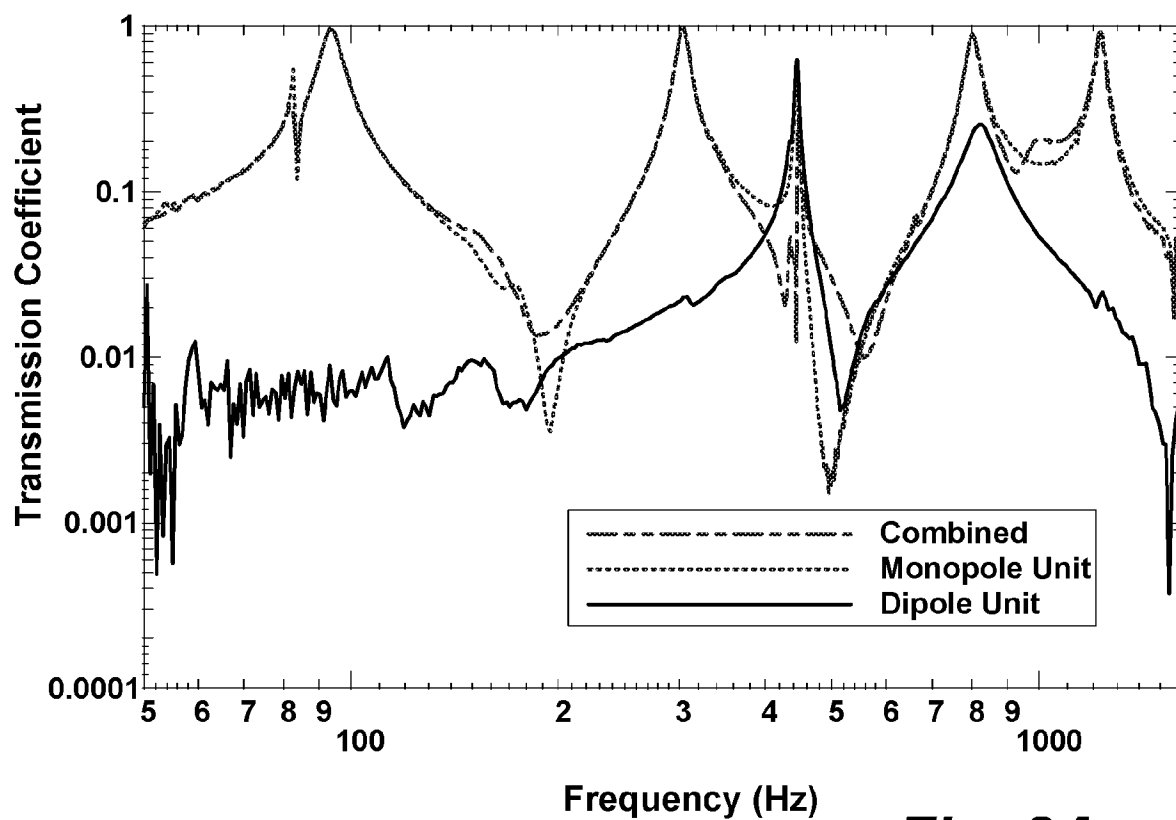
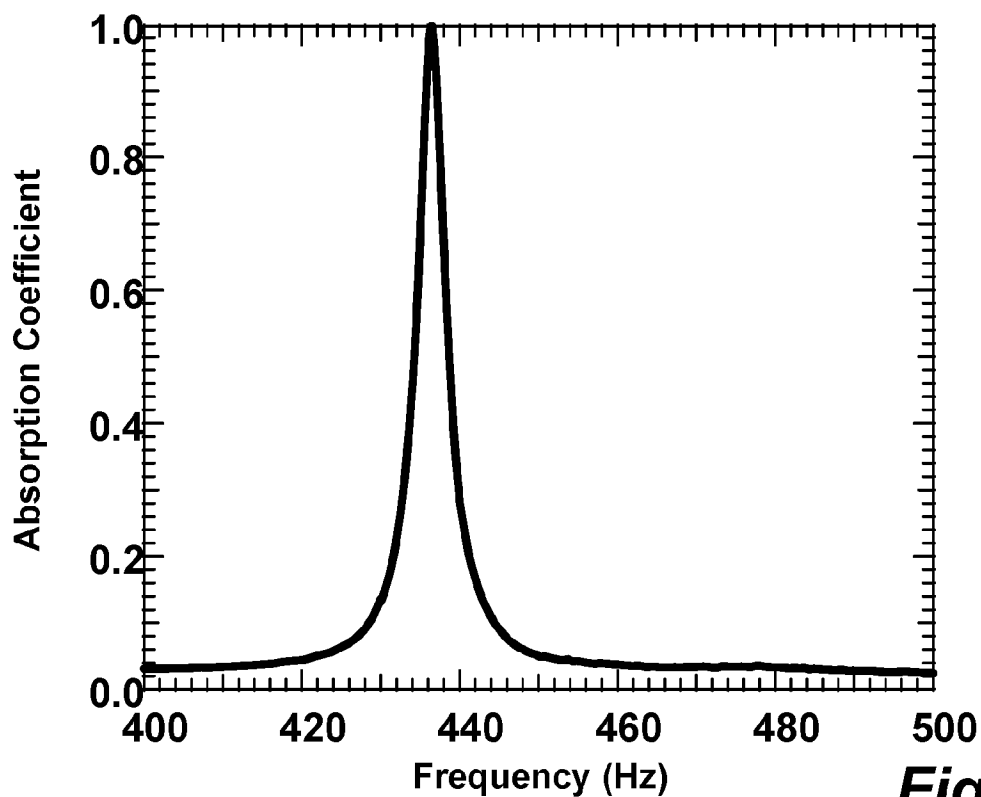
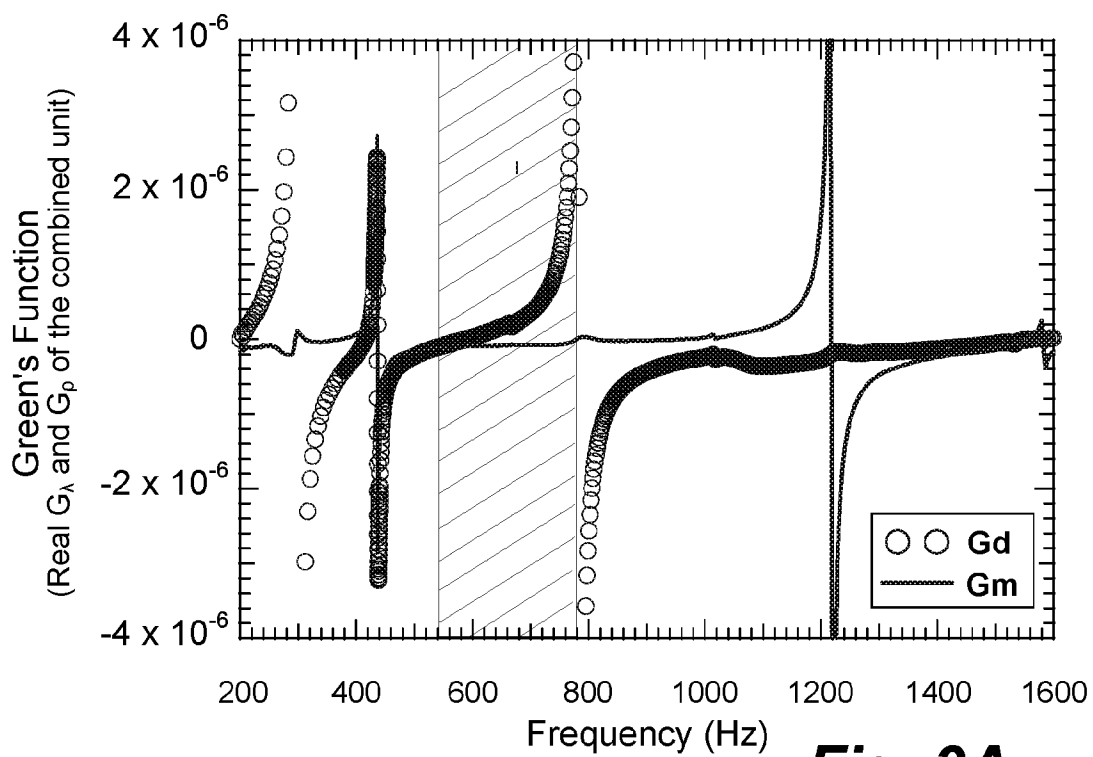
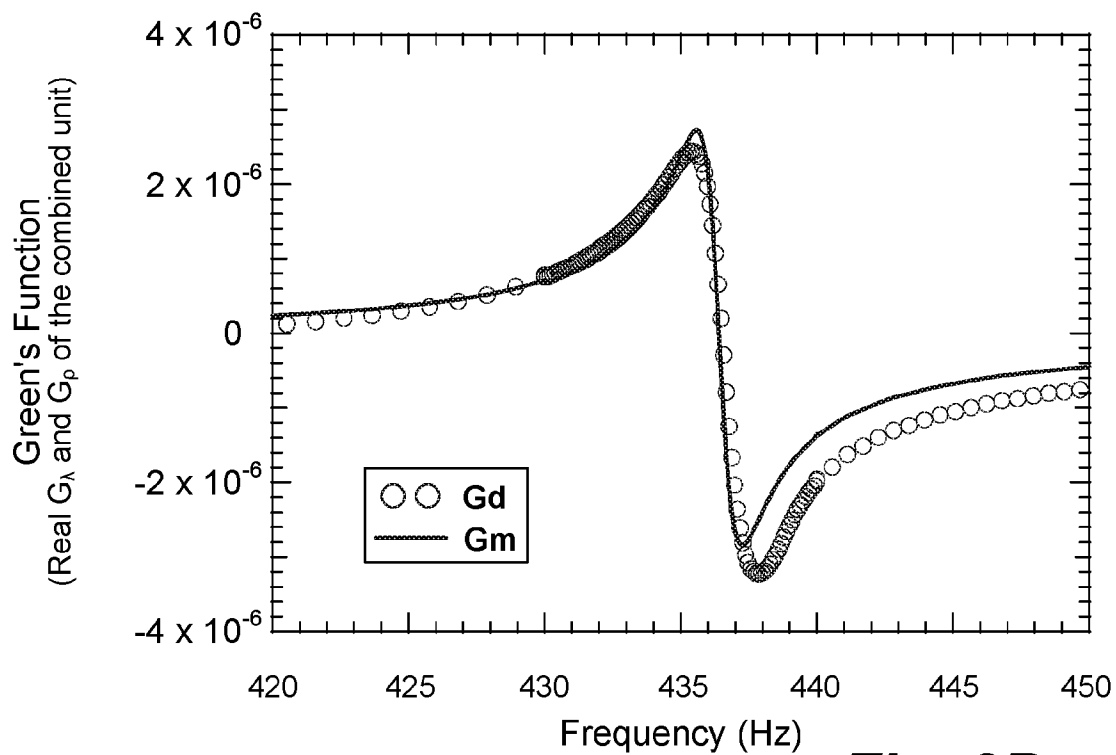


Fig. 1C

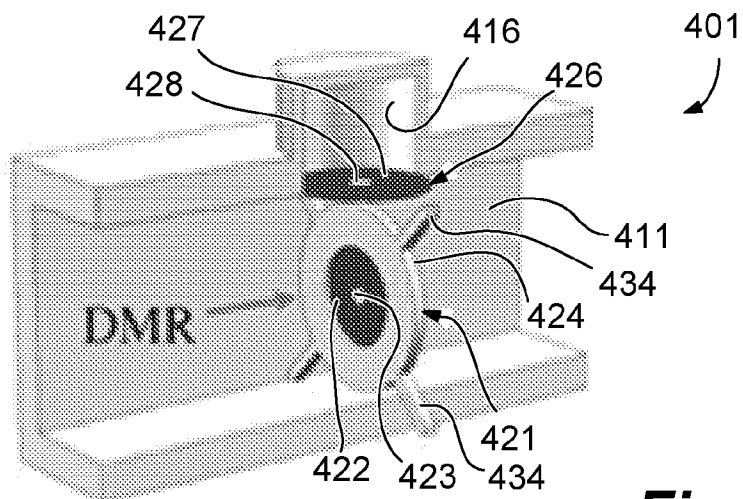
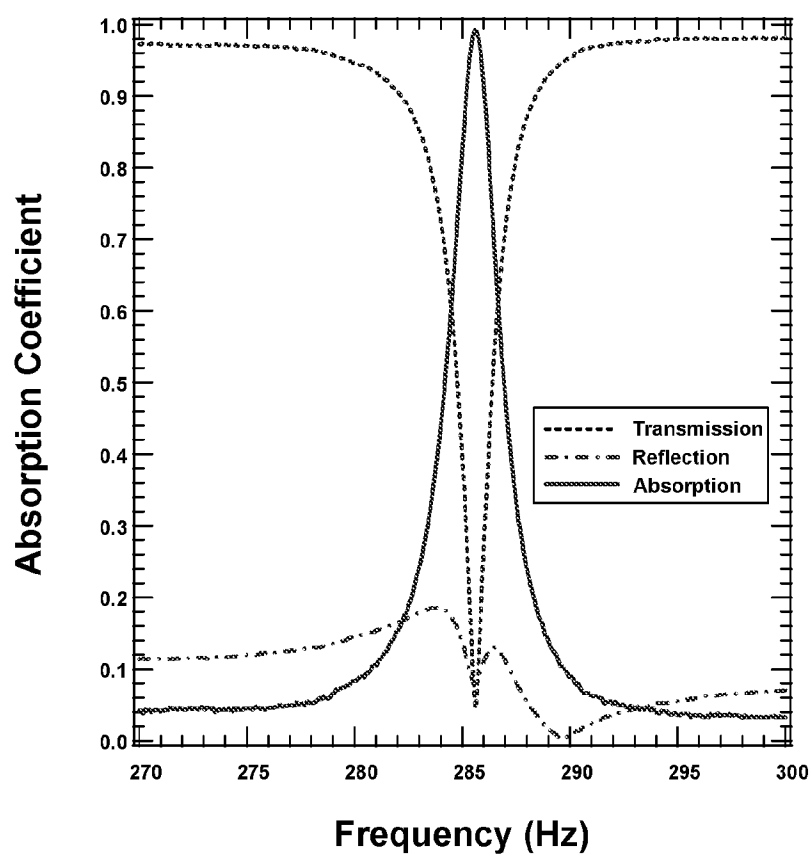
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**Fig. 2A****Fig. 2B**

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**Fig. 3A****Fig. 3B**

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**Fig. 4A****Fig. 4B**

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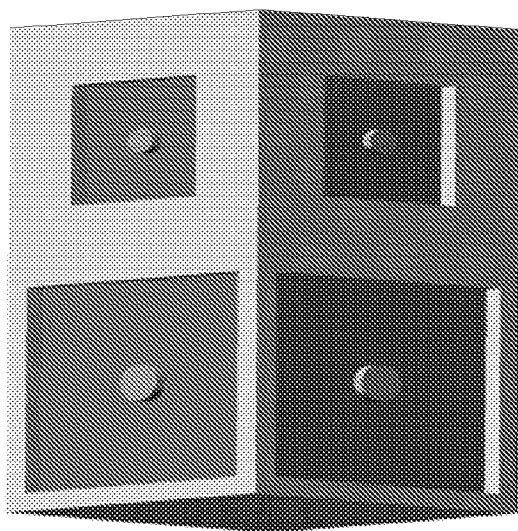


Fig. 5

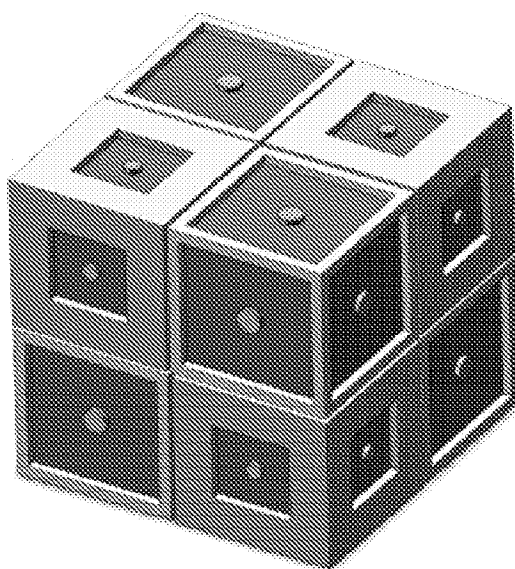


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2016/080464

A. CLASSIFICATION OF SUBJECT MATTER

G10K 11/172(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G10K11/-

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI,EPODOC,CNKI,CNPAT,ISI:sound,noise,tone,absor+,attenuat+,degenerat+, destruct+,metamaterial,dipole,dipolar, monopolar,monopole,resonat+,membrane, DMR,eigenmode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2014139323 A1 (THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY) 18 September 2014 (2014-09-18) description, paragraphs [0010], [0041]-[0046], [0053]-[0058], [0067]-[0072] and figures 1 to 4	1-14
A	CN 103996395 A (XI'AN JIAOTONG UNIVERSITY) 20 August 2014 (2014-08-20) the whole document	1-14
A	CN 103137118 A (THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY) 05 June 2013 (2013-06-05) the whole document	1-14
A	CN 103362229 A (NANJING UNIVERSITY) 23 October 2013 (2013-10-23) the whole document	1-14
A	CN 1664920 A (RSM TECHNOLOGIES LTD.) 07 September 2005 (2005-09-07) the whole document	1-14

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance
 “E” earlier application or patent but published on or after the international filing date
 “L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
 “O” document referring to an oral disclosure, use, exhibition or other means
 “P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
 “X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
 “Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
 “&” document member of the same patent family

Date of the actual completion of the international search

13 July 2016

Date of mailing of the international search report

21 July 2016

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2016/080464

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	YANG, Min et al. "Coupled Membranes with Doubly Negative Mass Density and Bulk Modulus." <i>PHYSICAL REVIEW LETTERS.</i> , 29 March 2013 (2013-03-29), the whole document	1-14
A	MEI, Jun et al. "Dark acoustic metamaterials as super absorbers for low-frequency sound." <i>NATURE COMMUNICATIONS.</i> , 27 March 2012 (2012-03-27), the whole document	1-14
A	YANG, Min et al. "Sound Absorption by Subwavelength Membrane Structures: A Generalized Perspective." <i>arXiv:1502.06358v1 [cond-mat.mtrl-sci]</i> , 23 February 2015 (2015-02-23), the whole document	1-14

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2016/080464

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
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