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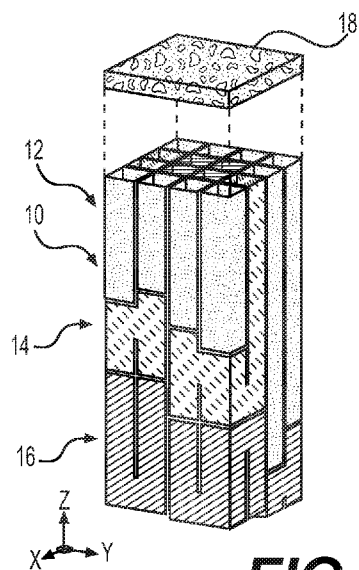
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(54) Title: ACOUSTIC METAMATERIAL SOUND ABSORBER

**FIG. 1**

(57) Abstract: The acoustic metamaterial sound absorber (10, 100, 300, 400, 500, 600, 700, 800, 900, 1000) is formed from an array of acoustic resonance cavities (310, 410). Each of the acoustic resonance cavities (310, 410) may be folded to have at least one inlet, an opposed closed end and at least two plies. A density of number of modes per unit frequency, D , associated with the array of acoustics resonance cavities (310, 410) is given by $D = 2/\pi[\alpha(\Omega)Z(\Omega)]$, where Ω is a resonant frequency of each mode associated with the array of acoustic resonance cavities (310, 410), $\alpha(\Omega)$ is an oscillator strength at the resonant frequency Ω , and $Z(\Omega)$ is a target impedance.

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ACOUSTIC METAMATERIAL SOUND ABSORBER**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims the benefit of U.S. Provisional Patent Application Serial No. 62/393,195, filed on September 12, 2016, U.S. Provisional Patent Application Serial No. 62/423,228, filed on November 17, 2016, U.S. Provisional Patent Application Serial No. 62/488,708, filed on April 22, 2017, and U.S. Provisional Patent Application Serial No. 62/557,141, filed on September 12, 2017.

TECHNICAL FIELD

The disclosure of the present patent application relates generally to resonant sound absorbers, and particularly to an acoustic metamaterial formed from arrayed, folded acoustic resonance cavities which provides broadband sound absorption.

BACKGROUND ART

Absorbing sound spontaneously converts part of the sound energy to a very small amount of heat in the intervening object (i.e., the absorbing material), rather than sound being transmitted or reflected. There are several ways in which a material can absorb sound and the choice of sound absorbing material is typically determined by the frequency distribution of noise to be absorbed and the acoustic absorption profile required. Sound absorbers typically fall into the two broad categories of porous absorbers and resonant absorbers. Porous absorbers, typically formed from open cell rubber foams or melamine sponges, absorb noise by friction within the cell structure. Porous open cell foams are highly effective noise absorbers across a broad range of medium-high frequencies, but is typically less efficient at lower frequencies. Resonant panels, Helmholtz resonators and other resonant absorbers work by damping a sound wave as they reflect it. Unlike porous absorbers, resonant absorbers are most effective at low-medium frequencies and the absorption of resonant absorbers is always matched to a narrow frequency range.

Given that porous absorbers and conventional resonant absorbers are effective for sound absorption within a certain frequency range only, they are difficult, if not impossible, to adapt to applications requiring broadband sound absorption. Although there has been a great deal of recent research in the field of locally resonant artificial structures, which have shown diverse functionalities in sound manipulation, even achieving highly efficient sound

absorption within a compact volume, the dispersive nature of the resonances in these structures still limits their applications to a generally narrow band. Thus, an acoustic metamaterial sound absorber solving the aforementioned problems is desired.

DISCLOSURE

5 The acoustic metamaterial sound absorber of the present subject matter is formed from an array of acoustic resonance cavities. A density of number of modes per unit frequency, D , associated with the array of acoustic resonance cavities is given by $D = \frac{2}{\pi[\alpha(\Omega)Z(\Omega)]}$, where Ω is a resonant frequency of each mode associated with the array of acoustic resonance cavities, $\alpha(\Omega)$ is an oscillator strength at the resonant frequency Ω , and
 10 $Z(\Omega)$ is a target impedance. $D = \frac{\Delta n}{\Delta \Omega}$ is the number of modes, n , per unit frequency.

Preferably, the array of acoustic resonance cavities has a minimum thickness, $d_{\min}$, defined by $d_{\min} = \frac{1}{4\pi^2} \frac{B_{\text{eff}}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|$, where λ is an acoustic wavelength in the air, $A(\lambda)$ is an absorption coefficient, B_{eff} is an effective bulk modulus of the array of acoustic resonance cavities in a static limit, and B_0 is a bulk modulus of the air. Typically, the bulk
 15 geometry of the acoustic metamaterial sound absorber will have a thickness of less than 100 cm, and does not exceed 110% of the minimum thickness, $d_{\min}$. Each of the acoustic resonance cavities may be folded, such that each acoustic resonance cavity has at least one inlet, an opposed closed end and at least two plies.

A sound absorbing layer, formed from a sound absorbing material, may be mounted
 20 on the array of acoustic resonance cavities and/or each of the acoustic resonance cavities may be at least partially filled with sound absorbing material. The sound absorbing material may be any suitable type of sound absorbing material. Non-limiting examples of the sound absorbing material include wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof. It should be understood that the acoustic resonance cavities may be
 25 any suitable type of acoustic resonator cavities, such as Fabry-Pérot cavities, Helmholtz cavities or the like.

In an alternative embodiment, the acoustic metamaterial sound absorber is formed from first, second and third arrays of Fabry-Pérot cavities. Each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities extends linearly and has an inlet and an outlet. Each
 30 of the Fabry-Pérot cavities of the second array of Fabry-Pérot cavities is folded to have at least one inlet, an opposed closed end and at least two plies, and each of the Fabry-Pérot

cavities of the third array of Fabry-Pérot cavities is folded to have at least one inlet, an opposed closed end and at least three plies. The second array of Fabry-Pérot cavities is sandwiched between the first array of Fabry-Pérot cavities and the third array of Fabry-Pérot cavities. A sound absorbing layer, such as an acoustic sponge, for example, is mounted on the first array of Fabry-Pérot cavities to cover the inlet of each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities.

In a particular embodiment, each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities extend linearly along a transverse axis, with the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities being arrayed in a square grid-wise pattern along a lateral axis and a longitudinal axis, where the transverse, lateral and longitudinal axes are mutually orthogonal with respect to one another.

These and other features of the present disclosure will become readily apparent upon further review of the following specification and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of an acoustic metamaterial sound absorber.

Fig. 2 is a graph showing oscillator strength of acoustic resonance channels of the acoustic metamaterial sound absorber at quarter-wavelength resonances.

Fig. 3 is a plot comparing surface impedance of the acoustic metamaterial sound absorber formed from only acoustic resonance channels and surface impedance of the acoustic metamaterial sound absorber with an additional layer of acoustic sponge.

Fig. 4 is a graph showing real and imaginary parts of surface impedance as a function of frequency for the acoustic metamaterial sound absorber.

Fig. 5 is a graph showing the absorption coefficient as a function of frequency for the acoustic metamaterial sound absorber.

Fig. 6A is a plot comparing the absorption spectrum of the acoustic metamaterial sound absorber formed from only acoustic resonance channels and the absorption spectrum of the acoustic metamaterial sound absorber with an additional layer of acoustic sponge.

Fig. 6B is a plot comparing the absorption coefficient of the acoustic metamaterial sound absorber formed from only acoustic resonance channels and the absorption coefficient of the acoustic metamaterial sound absorber with an additional layer of acoustic sponge.

Fig. 7 is a perspective view of an alternative embodiment of the acoustic metamaterial sound absorber.

Fig. 8 is a graph comparing the measured absorption spectrum of the acoustic metamaterial sound absorber of Fig. 7 against a simulated absorption spectrum.

Fig. 9A is a graph showing a noise spectrum measured from a conventional hairdryer.

Fig. 9B is a graph comparing measured and simulated results of transmission loss for
5 an acoustic silencer formed from the acoustic metamaterial sound absorber.

Fig. 10 is a perspective view of the acoustic silencer formed from the acoustic metamaterial sound absorber.

Fig. 11 is a front view in section of a first portion of the acoustic silencer of Fig. 10.

Fig. 12 is a perspective view of a second portion of the acoustic silencer of Fig. 11.

10 Fig. 13 is a perspective view of a third portion of the acoustic silencer of Fig. 12.

Fig. 14 is a perspective view of an alternative embodiment of the acoustic metamaterial sound absorber.

Fig. 15 is a perspective view of another alternative embodiment of the acoustic metamaterial sound absorber.

15 Figs. 16A, 16B, 16C, 16D, 16E and 16F are each sectional views of further alternative embodiments of the acoustic metamaterial sound absorber.

Figs. 17A, 17B and 17C are each sectional views of alternative folding configurations of the acoustic resonance channels of the acoustic metamaterial sound absorber.

20 Fig. 18 is a partial perspective view of yet another alternative embodiment of the acoustic metamaterial sound absorber.

Fig. 19 is a perspective view of still another alternative embodiment of the acoustic metamaterial sound absorber.

Similar reference characters denote corresponding features consistently throughout the attached drawings.

25 BEST MODES

The acoustic metamaterial sound absorber of the present subject matter is formed from an array of acoustic resonance cavities. As will be described in greater detail below, a density of number of modes per unit frequency, D , associated with the array of acoustic resonance cavities is given by $D = \frac{2}{\pi[\alpha(\Omega)Z(\Omega)]}$, where Ω is a resonant frequency of each mode
30 associated with the array of acoustic resonance cavities, $\alpha(\Omega)$ is an oscillator strength at the resonant frequency Ω , and $Z(\Omega)$ is a target impedance. $D = \frac{\Delta n}{\Delta \Omega}$ is the number of modes, n , per unit frequency.

Preferably, the array of acoustic resonance cavities has a minimum thickness, $d_{\min}$, defined by $d_{\min} = \frac{1}{4\pi^2} \frac{B_{\text{eff}}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|$, where λ is an acoustic wavelength in the air, $A(\lambda)$ is an absorption coefficient, B_{eff} is an effective bulk modulus of the array of acoustic resonance cavities in a static limit, and B_0 is a bulk modulus of the air. Typically, the bulk geometry of the acoustic metamaterial sound absorber will have a thickness of less than 100 cm, and which does not exceed 110% of the minimum thickness, $d_{\min}$. Each of the acoustic resonance cavities may be folded, such that each acoustic resonance cavity has at least one inlet, an opposed closed end and at least two plies. As will be described in greater detail below, the embodiment of Fig. 1 illustrates a non-limiting example utilizing both folded and non-folded resonance cavities.

A sound absorbing layer, formed from a sound absorbing material, may be mounted on the array of acoustic resonance cavities and/or each of the acoustic resonance cavities may be at least partially filled with sound absorbing material. The sound absorbing material may be any suitable type of sound absorbing material. Non-limiting examples of the absorbing material include wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof. It should be understood that the acoustic resonance cavities may be any suitable type of acoustic resonator cavities, such as Fabry-Pérot cavities, Helmholtz cavities or the like. In use, the sound energy, at the resonant frequencies and near the resonant frequencies, is efficiently guided into the resonant cavities and is dissipated due to the dissipation introduced by the friction and thermal conduction processes in the boundary layers at the inner walls of the cavities. The plurality of cavities constituting the array provide sufficient large resonant mode density for broadband sound absorption.

In the embodiment of Fig. 1, the acoustic metamaterial sound absorber 10 includes first, second and third arrays of Fabry-Pérot cavities. Each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities 12 extends linearly and has an inlet and an outlet. Each of the Fabry-Pérot cavities of the second array of Fabry-Pérot cavities 14 is folded to have at least one inlet, an opposed closed end and at least two plies, and each of the Fabry-Pérot cavities of the third array of Fabry-Pérot cavities 16 is folded to have at least one inlet, an opposed closed end and at least three plies. The second array of Fabry-Pérot cavities 14 is sandwiched between the first array of Fabry-Pérot cavities 12 and the third array of Fabry-Pérot cavities 16. A sound absorbing layer 18, such as an acoustic sponge, for example, is mounted on the first array of Fabry-Pérot cavities 12 to cover the inlet of each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities 12.

In the particular embodiment as shown, each of the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities 12 extend linearly along a transverse axis (i.e., the z-axis in Fig. 1), with the Fabry-Pérot cavities of the first array of Fabry-Pérot cavities 12 being arrayed in a square grid-wise pattern along a lateral axis (the x-axis) and a longitudinal axis (the y-axis), where the transverse, lateral and longitudinal axes are mutually orthogonal with respect to one another.

It should be understood that the overall contouring of the acoustic metamaterial sound absorber may be varied, and the cross-sectional contours of the individual acoustic resonance cavities may also vary. For example, as shown in Fig. 14, acoustic metamaterial sound absorber 300 has an overall square contour, with acoustic resonance cavities 310 having individual square cross-sectional contours. Fig. 15 illustrates another example, in which acoustic metamaterial sound absorber 400 has sinusoidal, or wave-like, contour, with acoustic resonance cavities 410 having individual rectangular cross-sectional contours. Figs. 16A, 16B, 16C, 16D, 16E and 16F illustrate further examples, with acoustic metamaterial sound absorbers 500 and 600 each having individual square resonance cavity cross-sectional contours, where the cavities are arrayed in a grid-type pattern in acoustic metamaterial sound absorber 500, and where the cavities are linearly arrayed in acoustic metamaterial sound absorber 600. Further, exemplary acoustic metamaterial sound absorbers 700, 800, 900 and 1000 have cavities which are, respectively, circular, hexagonal, linearly arrayed and tessellated.

Additionally, it should be understood that numerous different foldings are possible for the acoustic resonance cavities. For example, array 1100 of Fig. 17A illustrates cavities with a two-dimensional folding with a constant cross-sectional area. Array 1200 of Fig. 17B illustrates an exemplary two-dimensional folding with a changing cross-sectional area. In Fig. 17C, array 1300 has a cavity folding with two open ends. Further, it should be understood that the three-dimensional folding of Fig. 1 is only an example of one type of structure making use of folded acoustic resonance cavities. Figs. 18 and 19 illustrate exemplary arrays 1400 and 1500 which make use of a two-dimensional folding of acoustic resonance cavities.

Material response functions for electromagnetic and acoustic waves must satisfy the causality principle. For electromagnetic waves, the causal nature of the material response function has been found to result in an inequality that relates a given absorption performance to the sample thickness. Adapted to acoustics, this relation (for sound waves propagating in

air) can be expressed in the following form for a flat absorbing material (or structure) with thickness d sitting on a reflecting substrate:

$$d \geq \frac{1}{4\pi^2} \frac{B_{eff}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|, \quad (1)$$

where λ represents the sound wavelength in air, $A(\lambda)$ is the absorption coefficient, $B_{eff} = -V \frac{\Delta p}{\Delta V}$ denotes the static effective bulk modulus of the sound absorbing structure, with V being the volume at static condition and p being the pressure statically applied, and B_0 is the bulk modulus of air. Herein, a sound absorbing structure is considered to be optimal if equality or near-equality can be attained in equation (1). Some obvious implications immediately follow from equation (1); e.g., total absorption within a finite frequency range is not possible for any finite thickness sample. Also, high absorption at low frequencies would dominate the contribution to sample thickness. However, $A(\lambda) \sim 1$ at a low frequency is entirely possible for a very subwavelength sample thickness, provided that the absorption peak is narrow.

As will be shown, the acoustic metamaterial sound absorber 10 achieves near-equality in the causal relation of equation (1) with a flat, near-perfect absorption spectrum starting at 400 Hz. In particular, the right-hand side of equation (1) is shown to yield 11.5 cm, while the actual sample thickness is 12 cm. A similar optimal sample, with $d = 6$ cm, has been fabricated that displayed the same flat, near-perfect absorption spectrum above 800 Hz.

Considering a layer of acoustic sponge with thickness h sitting on a reflecting surface, since a node must exist at the reflecting surface, high absorption becomes possible only when $\frac{\lambda_s}{4} < h$, so that there is appreciable wave amplitude inside the sponge. Here, λ_s represents the wavelength in the sponge. In contrast, if the sponge is backed by a soft boundary, then an anti-node exists at the substrate boundary, and the absorption for $\frac{\lambda_s}{4} > h$ becomes much better than that for the hard boundary, owing to the larger wave amplitude inside the sponge. However, the soft boundary is not optimal. Near-perfect absorption would occur only when there is impedance matching so that there is no reflection. Thus, impedance matching with air, such that $Z_0 = \rho_0 v_0$, is the goal for optimization. Here, 343 m/s is the speed of sound in air (v_0), and ρ_0 is the density of air.

To realize the optimal backing to a thin layer of sponge, a pre-designed acoustic metamaterial is used which is constrained by the objective $A(\lambda)$, which is ~ 1 above a low frequency cutoff. The impedance of a planar resonator at the resonance frequency is close to

zero, thus it can approximate a soft boundary. For an acoustic metamaterial with multiple resonances, the total impedance, Z , can be expressed as:

$$Z = \frac{i}{\omega} \left(\sum_n \frac{\alpha_n}{\Omega_n^2 - \omega^2 - i\beta\omega} \right)^{-1}, \quad (2)$$

where $Z \equiv p/v$ denotes the surface impedance, with p being the pressure, v being the displacement velocity in response to the pressure at the surface of the metamaterial, ω being the angular frequency, Ω_n denoting the n^{th} resonance frequency, α_n being its oscillator strength, and $\beta \ll \omega$ describing the weak system dissipation for the acoustic metamaterial. The definition of the oscillator strength is given below. For equation (2) to be an accurate description of the acoustic metamaterial, the lateral size of the metamaterial units, assuming them to be periodically arranged, must be very subwavelength in scale so that the diffraction effects can be neglected.

In the idealized case where there is a continuum distribution of resonances, equation (2) can be converted to an integral as:

$$Z \cong \lim_{\beta \rightarrow 0} \frac{i}{\omega} \left(\int_{\Omega_1}^{\infty} \frac{\alpha(\Omega)D(\Omega)}{\Omega^2 - \omega^2 - i\beta\omega} d\Omega \right)^{-1}. \quad (3)$$

In equation (3), the imaginary part of the impedance is generally negligible, owing to the oscillatory nature of the real part of the integrated in the square bracket. In the limit of $\beta \rightarrow 0$, the imaginary part of the integration is essentially a delta function, thus resulting in $Z(\omega) \approx \frac{1}{\pi\omega} \left[\int_0^{\infty} \alpha(\Omega)D(\Omega)\delta(\omega^2 - \Omega^2) d\Omega \right]^{-1} = \frac{2}{\pi} [\alpha(\omega)D(\omega)]^{-1}$. By definition, $D(\Omega) = \lim_{\Delta\Omega \rightarrow 0} \frac{\Delta n}{\Delta\Omega}$, thus yielding:

$$\frac{d\Omega}{dn} = \frac{\pi}{2} Z(\Omega) \alpha(\Omega). \quad (4)$$

Equation (4) describes the necessary mode distribution to achieve the targeted impedance $Z(\Omega)$.

By specifying the oscillator strength $\alpha(\Omega)$, the differential equation (4) can be solved with an initial condition of $\Omega = \Omega_1$, in conjunction with the input $Z(\omega)$ obtained from the target absorption spectrum $A(\omega)$ for $\omega > \Omega_1$, i.e., $Z(\omega) = Z_0(2 - A(\omega) \pm 2\sqrt{1 - A(\omega)})/A(\omega)$. It should be noted that there are two sets of solutions of $Z(\omega)$ and they can both achieve the target absorption spectrum.

For an acoustic metamaterial with a given cross-sectional dimension, it is difficult to avoid a choppy absorption spectrum with large swings of high absorption followed by deep valleys. However, it is shown below that a thin layer of acoustic sponge in front of the acoustic metamaterial array can qualitatively alter the nature of absorption, leading to a flat

absorption spectrum similar to the idealized case with a low frequency cutoff. Such an effect has been previously observed in a one-dimensional array of slit channels with a wire mesh placed on top. Below, a quantitative theory for such an effect is provided, as well as a general design strategy and the optimality perspective based on causality.

5 As a non-limiting example, the cross-section of the acoustic metamaterial sound absorber 10 of Fig. 1 is considered to have a periodic two-dimensional square lattice with a periodicity of $L = 4.55$ cm; i.e., in this example, the side length of the lateral-longitudinal square cross-section, L , is 4.55 cm. It should be understood that Fig. 1 illustrates only a single unit, or cell, of what may be a larger array of such sound absorbers 10. Although a
 10 variety of local resonators, such as decorated membranes, can be used to design the metamaterial unit 10, sound absorber 10 utilizes Fabry-Pérot (FP) resonators in which $B_{eff} = B_0$. Within each unit 10 in this example, there are 16 FP channels, each with a square cross-section that is ~ 1.038 cm on each side, separated from each other with a 1 mm thick wall. The first order FP resonance frequency of the n th channel is given by $\Omega_n = \frac{\pi v_0}{2l_n}$, where
 15 l_n denotes its channel length. For simplicity, the contributions of higher order FP resonances are ignored in the design process; their effect is mostly at higher frequencies and will be discussed below. If $n = 1$ denotes the longest channel, so that $\Omega_1 = 2\pi \times 372.8$ Hz is the lowest resonance frequency, then the position of each channel in the unit is shown in Fig. 1, where the (first order) resonance frequency of each channel increases with increasing n .

20 As noted above, the longer channels (i.e., the second array 14 and the third array 16) are folded in order to obtain a compact structure that can approach the thickness $\bar{d} = \sum_{n=1}^{16} \frac{l_n}{16}$. The folding, which was designed by computer simulations, can be seen for the second array 14 and the third array 16. In this example, each channel, or cavity, of the second array 14 is folded twice, and each channel, or cavity, of the third array 16 is folded three times. In this
 25 particular example, given the exemplary figures above, $\bar{d} = 10.58$ cm, whereas the actual produced sample, with folded channels, had a thickness of $d = 11.06$ cm. The relevant normalized eigenmode is given by $\varphi_n(z) = \sqrt{\frac{4\Omega_n}{\pi v_0}} \cos\left(\frac{\pi z}{2l_n}\right)$, where $z = 0$ defines the front surface of the metamaterial unit 10. In response to applied pressure, the z component air displacement velocity, v_n , at the mouth of the n^{th} channel, $z = 0$, is given by $v_n = -i\omega g_n p_n$,
 30 where p_n denotes the local pressure value, and g_n is the Green function defined by:

$$g_n = \frac{\phi}{16} \frac{|\varphi_n(0)|^2 / \int_0^{l_n} |\varphi_n(z)|^2 \rho(z) dz}{\Omega_n^2 - \omega^2 - i\beta\omega}, \quad (5)$$

where $\rho(z)$ is the local mass density and ϕ the ratio of the cavities' total open cross-sectional area over the total area. Here, only the first order FP resonance is considered. In actual calculations, all of the higher orders are included. The numerator of g_n is proportional to the oscillator strength, $\alpha_n = \phi |\varphi_n(0)|^2 / \left[16 \int_0^{l_n} |\varphi_n(z)|^2 \rho(z) dz \right]$. Since, in the present case, $\rho(z) = \rho_0$, it follows that $\alpha_n = \frac{\phi \Omega_n}{4\pi Z_0}$, which is shown in Fig. 2 for the 11 of the 16 resonance frequencies obeying the rule $\Omega_n = \Omega_1 e^{\phi(n-1)/8}$, with $\Omega_{16} = 2431$ Hz and $\phi = 0.832$, as derived below. This rule is designed so that the mode density $D_n = \left(\frac{\partial \Omega_n}{\partial n} \right)^{-1} = 8\phi^{-1} \Omega_n^{-1}$, which leads directly to the desired $\mu = \alpha_n D_n = \frac{2}{\pi Z_0}$, as taught by the idealized case for achieving a constant impedance Z_0 . Given the value of Ω_n , the n^{th} channel length is uniquely determined. The arrangement of the 16 channels within the metamaterial unit 10 (shown in Fig. 1) is optimized subject to the geometric requirements of channel folding.

Impedance that is flat in frequency and close to the air impedance $Z_0 = \rho_0 v_0$ starting at a lower cutoff frequency Ω_1 is targeted. The solution of equation (4) is just $\Omega_n = \Omega_1 e^{\phi(n-1)/8}$, and the integral equation (3) can be integrated to yield:

$$Z = \frac{\pi Z_0}{\pi - 2i \tanh^{-1}\left(\frac{\Omega_1}{\omega}\right)}. \quad (6)$$

The behavior for the real and imaginary parts of Z are shown in Fig. 4. The imaginary part, owing to the oscillatory nature of the integrand in equation (3), rapidly decays to zero for $\omega > \Omega_1$. However, the real part of the impedance is seen to approach the impedance matching condition $\frac{Z}{Z_0} = 1$ beyond Ω_1 . The absorption spectrum can be calculated by:

$$A = 1 - \left| \frac{\left(\frac{Z}{Z_0}\right) - 1}{\left(\frac{Z}{Z_0}\right) + 1} \right|^2 = 1 - \left| \frac{\tanh^{-1}(\Omega_1/\omega)}{\pi - i \tanh^{-1}(\Omega_1/\omega)} \right|^2, \quad (7)$$

which is plotted in Fig. 5. By substituting $A(\lambda)$, as expressed by equation (7), into equation (1), with $\lambda = \frac{2\pi v_0}{\omega}$ and $B_{eff} = B_0$, then $d \geq \frac{\lambda_1}{\pi^2}$, with $\lambda_1 \equiv \frac{2\pi v_0}{\Omega_1}$. Thus, for a cutoff frequency of $\frac{\Omega_1}{2\pi} = 312$ Hz, there is a minimum sample thickness of ~ 11.1 cm. Thus, it can be seen from this idealized case that flat impedance as a function of frequency requires the mode density to be inversely proportional to the oscillator strength.

The above is an example of a broadband absorber, where the targeted absorption spectrum can be expressed as $A = 1$ when $\Omega > \Omega_1$. This leads a flat impedance, where $Z = Z_0$ ($\Omega > \Omega_1$) and $Z = 0$ ($\Omega < \Omega_1$). Under the initial condition of $\Omega = \Omega_1$ at $n = 1$, then $\Omega_n = \Omega_1 e^{2\phi(n-1)/N}$. Thus, $\alpha(\Omega)D(\Omega) = 2/(\pi Z_0)$ becomes a constant for $\Omega > \Omega_1$, which

allows the above integral for $Z(\omega)$ to be rewritten as $\frac{Z(\omega)}{Z_0} = \frac{\pi}{\pi - 2i \tanh^{-1}(\Omega_1/\omega)}$. The behavior for the real and imaginary parts of Z is shown in Fig. 4. The imaginary component rapidly decays to zero for $\Omega > \Omega_1$ due to its oscillatory nature. The real part is seen to approach impedance matching condition $Z = Z_0$ beyond Ω_1 . The corresponding absorption spectrum can be evaluated as equation (7) above. In this idealized case, just the acoustic metamaterial alone can achieve near-perfect broadband absorption, requiring only an infinitesimal dissipation coefficient, which can be realized by the viscous friction between the air and the hard wall of the air cavities.

By substituting $A(\lambda)$ from equation (7) into equation (1), with $\lambda = 2\pi v_0/\omega$ and $B_{eff} = B_0/\phi$ as noted above, the resultant expression is $d_{min} = 2v_0/(\pi\phi\Omega_1)$. Since each first order FP resonance frequency is associated with a channel length $l_n = \pi v_0/(2\Omega_n)$, from volume conservation of the FP channels, assuming that the longer channels can be folded so as to form a compact volume, the optimal thickness is given by $\bar{d} = \sum_1^N \frac{l_n}{N} = [1 - e^{-2\phi}] \pi v_0/(4\phi\Omega_1)$. By letting $\bar{d} = d_{min}$, a value of $\phi_c = 0.832$ is obtained in this particular case. In this manner, the causal optimality is explicitly built into the design method to minimize the sample thickness, which is always crucial for comparison between different absorption samples, as well as for their practical applications.

It is important to note that the folding of the cavities should not change the front surface area exposed to the incident wave; i.e., the value of ϕ should remain unchanged after channel folding. Since d_{min} is evaluated with the target absorption spectrum, the condition of $d_{min} = d$ is also a consistency condition for optimally achieving the target absorption spectrum.

A sample metamaterial unit was fabricated using 3D printing with UV-sensitive epoxy. Reflection measurements from four such units were taken, with the four units being arranged in a square and placed against a reflecting wall. The measurements were carried out using an impedance tube with a square cross-section that was 9 cm on each side, with a length of 44.75 cm. Two microphone detectors were used to measure the amplitude and phase of the waves, from which the reflection coefficient $R = \frac{Z/Z_0 - 1}{Z/Z_0 + 1}$, as well as the impedance of the sample could be deduced. The impedance tube had a cutoff frequency between 1400 and 1500 Hz, beyond which the measured results are inaccurate. The measured impedance is shown by the circles (1) in Fig. 3. It can be seen that circles (1) (i.e., the impedance measurements for just the FP channels) oscillate around Z_0 with peaks and

valleys. This is expected, since there are 16 discrete resonances, and the impedance peaks can be associated with the anti-resonances that are in between the neighboring resonances. In fact, by treating each FP channel to be independent from the others, the impedance of the unit, denoted by Z_{bare} , can be written as:

$$Z_{bare} = \frac{i}{\omega} \left(\frac{1}{16} \sum_{n=1}^{16} g_n \right)^{-1}, \quad (8)$$

in analogy with equation (2). It can be seen that Z_{bare} displays oscillations in a similar fashion as the measured results. However, if a 1 cm layer of acoustic sponge is placed on top of the unit, then the impedance is shown by the circles (2) in Fig. 3. It can be seen that the oscillations almost completely vanish. Below, the origin of this effect is shown to be due to the evanescent waves that laterally couple the v_n 's at the mouths of different FP channels, and their interaction with a highly dissipative medium.

For frequencies much less than 7.5 kHz, $L \ll \lambda$. In this regime, not only the angular effect of the incident wave would be minimal, but also the observed impedance of the unit should be the homogenized effective value. At $z = 0$, the unit's surface has different local impedances, owing to the different FB channel length. This implies that the pressure should be most generally written as $p(\mathbf{x})$, where $\mathbf{x} = (x, y)$ denotes the lateral coordinate, so as to reflect this inhomogeneity. By writing $(\mathbf{x}) = \bar{p} + \delta p(\mathbf{x})$, where $\bar{p}$ denotes the value of $p(\mathbf{x})$ averaged over the surface area of the unit, and $\delta p(\mathbf{x})$ represents whatever is leftover. The $\delta p(\mathbf{x})$ component averages to zero over the surface area of the unit, and it can only couple to the evanescent waves that decay exponentially away from $z = 0$. This is because, from the dispersion relation, $|\mathbf{k}_{\parallel}|^2 + k_{\perp}^2 = \left(\frac{2\pi}{\lambda}\right)^2$, and since the $\mathbf{k}_{\parallel}$ components from the Fourier transform of $\delta p(\mathbf{x})$ must be larger than $\frac{2\pi}{\lambda}$ (since $L \ll \lambda$), it follows that $k_{\perp}^2 < 0$, hence evanescence along the z direction. In contrast, the $\mathbf{k}_{\parallel}$ components of $\bar{p}$ are peaked at $|\mathbf{k}_{\parallel}| = 0$, hence $\bar{p}$ couples to the propagating modes.

From the above, the impedance measured at far field is expected to be given by $Z = \frac{\bar{p}}{\bar{v}}$, where $\bar{v} = \sum_{n=1}^{16} \frac{v_n}{16}$. However, locally, the following must be true:

$$v_n = -i\omega g_n(\bar{p} + \delta p_n), \quad (9)$$

where δp_n represents the value of $\delta p(\mathbf{x})$ at the n^{th} FP channel location. It should be noted that even though $\sum_{n=1}^{16} \delta p_n = 0$, $\sum_{n=1}^{16} g_n \delta p_n \neq 0$. Therefore, it is clear that the lateral inhomogeneity can contribute to the renormalization of the bare impedance. To continue, $\delta p(\mathbf{x})$ is expanded in terms of the normalized Fourier basis functions $f_{\alpha} = e^{\frac{ik_{\alpha}x}{L}}$, where

$\alpha = (\alpha_x, \alpha_y)$ is discretized by the condition that the integral of f_α over the surface of the metamaterial unit must vanish. This means that $|\mathbf{k}_\alpha| = \frac{2\pi}{L} \sqrt{\alpha_x^2 + \alpha_y^2}$, where $\alpha_x, \alpha_y = \pm 1, \pm 2, \dots$. Since $\delta p(\mathbf{x})$ is coupled to evanescent waves, each Fourier component must be associated with a z -variation given by $e^{-\sqrt{|\mathbf{k}_\alpha|^2 - (2\pi/\lambda)^2}z}$. This implies a non-zero z -derivative of $\delta p(\mathbf{x}, z)$ which can couple to the v_n 's. Thus,

$$\delta p_n = i\omega\rho_0 \sum_m \Lambda_{nm} v_m, \text{ and} \quad (10a)$$

$$\Lambda_{nm} = 16 \sum_\alpha \frac{\sin^2(\alpha_x \pi/4) \sin^2(\alpha_y \pi/4)}{\pi^4 \alpha_x^2 \alpha_y^2 |\mathbf{k}_\alpha|} e^{i\mathbf{k}_\alpha \cdot (\mathbf{x}_m - \mathbf{x}_n)}, \quad (10b)$$

where $\mathbf{x}_n$ is the coordinate of the center of the n^{th} channel at $z = 0$, $\delta p_n = \delta p(\mathbf{x}_n)$, $v_m = v(\mathbf{x}_m)$, and $|\mathbf{k}_\alpha| \gg \frac{2\pi}{\lambda}$. By substituting equations (10a) and (10b) into equation (9), one obtains:

$$v_n = -\omega(g_n + \omega^2 \rho_0 \sum_m g_n \Lambda_{nm} g_m + \dots) \bar{p} \quad (11a)$$

$$v_n = -i\omega \left[g_n + \left(\omega^2 \rho_0 g_n^2 \Lambda_{nn} + \omega^4 \rho_0^2 g_n^3 \Lambda_{nn}^2 + \dots \right) + \omega^2 \rho_0 \sum_{m \neq n} g_n \Lambda_{nm} g_m + \dots \right] \bar{p} \quad (11b)$$

$$v_n = -i\omega \left(g_n + \frac{\omega^2 \rho_0 g_n^2 \Lambda_{nn}}{1 - \omega^2 \rho_0 g_n \Lambda_{nn}} + \sum_m \Pi_{nm} \right) \bar{p}. \quad (11c)$$

The series has been rearranged by separating out the terms involving Λ_{nn} , since $\Lambda_{nn} \gg \Lambda_{nm}$ by orders of magnitude. Numerically, the last term in the bracket is also small and thus constitutes a small adjustment in the result. By summing over n on both sides, it can be easily seen that $\frac{1}{Z} = \frac{1}{Z_{\text{bare}}} + \frac{1}{\delta Z}$, where

$$\delta Z = \frac{16i}{\omega} \left(\sum_n \frac{\omega^2 \rho_0 g_n^2 \Lambda_{nn}}{1 - \omega^2 \rho_0 g_n \Lambda_{nn}} + \sum_n \sum_m \Pi_{nm} \right)^{-1}. \quad (12)$$

From equation (11c), the evanescent wave effect is clearly seen in the appearance of the second term in the bracket. The resonances of the independent FP channels are identifiable by the frequencies at which the g_n 's diverge. From equation (11c) and the definition of the impedance, the renormalized resonance should be at the frequency which yields divergence of the coefficient in front of $\bar{p}$. If the first two terms inside the bracket of

equation (11c) are added, the result is a renormalized Green function given by $\frac{1}{g_n^{-1} - \omega^2 \rho_0 \Lambda_{nn}}$,

thus the resonance should occur at a frequency slightly below Ω_n , where the real part of $g_n^{-1} = \omega^2 \rho_0 \Lambda_{nn}$. In all of the above calculations, $\rho_0(1 + i\beta/\omega)$ has been used for the density of air, where $\beta = 14.2$ Hz serves to model the small air dissipation. Fig. 3 shows the excellent agreement between the calculated and measured impedance.

Fig. 6A shows the measured absorption of the metamaterial unit 10. The solid curve is calculated using equation (11c) to evaluate the Z and the reflection coefficient R , from which $A = 1 - |R|^2$. Very good agreement between theory and experiment can be seen in Fig. 6A. Here, the peaks in absorption are located at those frequencies where impedance matching is attained. The absorption spectrum of the FP channels can be evaluated to be sub-optimal in character, even though the lower cutoff characteristic is clearly visible. To improve the absorption performance, 1 cm of sponge was added in front of the metamaterial unit. The separately measured absorption of a 1 cm thick sponge is also shown in Fig. 6A. To model the result, the sponge is treated as a uniform medium with a bulk modulus the same as that of air, justified by the fact that the sound predominantly travels through the pores. The fitted sponge mass density is given by $\rho_{sponge} = [1.4 + i(1420 \text{ Hz})/\omega]\rho_0$. Here, the real part, $1.4\rho_0$, can be interpreted as being due to the tortuosity of the pores, which lengthens the time of travel and hence an effectively lower sound speed. The imaginary part, which is two orders of magnitude larger than that for air, is due to the small size of the pores and the inevitably larger viscous boundary layer dissipation.

The significantly larger imaginary part of the sponge mass density has a dramatic effect on the real part of the impedance. This can be seen from equations (11c) and (12) by replacing ρ_0 by ρ_{sponge} , so that the total impedance of the combined sponge and metamaterial unit is given by:

$$Z = \frac{i}{\omega} (G^{(e)})^{-1} = \frac{i}{\omega} \left(\frac{1}{16} \sum_{n=1}^{16} g_n^{(e)} \right)^{-1}, \quad (13)$$

where the small contributions of Π_{nm} and $(g_n^{(e)})^{-1} = g_n^{-1} - \omega^2 \rho_{sponge} \Lambda_{nn}$ are neglected. With the large imaginary part of ρ_{sponge} , at both the resonances and anti-resonances of the combined system the real part of $G^{(e)}$ would be zero, leaving only a nonzero imaginary part. As a result, there is a positive real part for Z that is nearly flat as a function of frequency, owing to the designed mode density rule discussed earlier. This can be seen in Fig. 3, which was calculated from equations (11c) and (12) (the Π_{nm} contributions included). It should be noted that in order to remedy the effect of higher order FP resonances of the longer channels, which lowers the impedance at higher frequencies to a value slightly below Z_0 , 0.5 mm of sponge was inserted in channels 10-16. This had a positive smoothing effect on the impedance, without altering the designed resonance frequencies. In modeling, this added

sponge was accounted for by increasing the dissipation coefficient β of channels 10-16 by a factor of 3.3.

Fig. 6B shows the absorption performance of the combined system, formed from 1 cm of sponge in front of the metamaterial unit. While the designed cutoff frequency is 312 Hz, there is an absorption tail below that, differing from the idealized case. Above the cutoff frequency, the absorption reaches 90% at 400 Hz, then increases beyond that to an essentially flat, near-perfect absorption all the way to higher frequencies. The agreement between theory and experiment is excellent. Simulation results show that beyond 1400 Hz, the very high absorption is maintained with no sign of dropping; this is due to the fact that the shorter wavelength at higher frequencies, plus the plurality of higher order FP resonances (which makes the metamaterial unit's impedance low), ensures the thin sponge layer absorption to be more effective than what is usually expected. By using the experimental absorption spectrum below 1400 Hz and the simulation results above that, the right-hand side of equation (1) is evaluated to be 11.5 cm, whereas the sample thickness was 12 cm. However, if the channel folding can be improved so that the limit of $\bar{d} = 10.58$ cm is reached, then the total thickness would be 11.58 cm; i.e., equation (1) essentially becomes equality.

Alternatively, one may begin by considering the array of FP channels, where the mode distribution inherently implies a minimum thickness of the sample, since $\Omega_n = \pi v_0 / (2l_n)$, and by volume conservation the minimum thickness of the sample is given by $\bar{d} = \sum_{n=1}^N l_n \phi / (N \phi_m)$, provided each channel's cross section is the same and ϕ_m represents the maximum porous ratio when the thickness of the wall and side length of the resonators have been given. Requiring $\bar{d} = d_{min}$, as evaluated from the causality constraint equation, yields $d_{min} = \frac{1}{4\pi^2} \frac{B_{eff}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|$, which leads to a unique value of ϕ .

To demonstrate the ability to achieve any desirable absorption spectrum, an exemplary spectrum, having a quasi-M-shape, is selected, such that:

$$A(f) = \begin{cases} 0.77 + 0.23 \cos\left[\frac{2\pi(f-f_0)}{f_0}\right]; & \text{when } f \in [f_0, 2f_0] \\ 0; & \text{when } f \notin [f_0, 2f_0] \end{cases} \quad (14)$$

For this example, a compact structure formed from 20 folded Fabry-Pérot (FP) channels is used, which possess a square cross-section that is 8.1 mm on each side, with a separating wall having a thickness of about 1 mm. The total area of the cross section is 90 mm X 90 mm, with a porous ratio of $\phi \approx 0.162$ at its front surface. Fig. 7 shows such an acoustic metamaterial sound absorber 100 formed from 20 folded FP channels 110.

From the above, the required surface impedance $Z(\omega)$ can be obtained. Then, by setting the initial frequency $\Omega_1 = 2\pi f_0 = 2\pi * 150$ Hz, the resonant frequencies Ω_n can be determined, along with the corresponding length l_n for the other 19 FP tubes. This is calculated by solving $\frac{d\Omega}{dn} = \frac{\pi\alpha(\Omega)Z(\Omega)}{2}$. The minimum thickness of the sample can then be

5 calculated as $\bar{d} = \sum_{n=1}^{20} l_n \times \frac{0.162}{20*0.81} = 81.9$ mm, whereas the actual sample thickness is 91.8 mm, due to the extra thickness of the back wall (4 mm) and further adjustment in total depth to compensate the acoustic effect by folding the structure. The measurement results for the actual fabricated sample are shown in Fig. 8. Good agreement is seen between the experimental result and the result from a Full-Wave simulation. The experimental result can

10 be seen to coincide well with the target spectrum. Further improvements are possible by increasing the total number of FP resonators so as to enhance the resolution in the working frequency region.

Fig. 10 shows a silencer 200 for hairdryers or the like which makes use of the acoustic metamaterial sound absorber. Silencer 200 is designed to block noise in a ventilated system,

15 such as in a hairdryer, by targeting the frequency spectrum with the highest sound energy concentration. The acoustic metamaterial sound absorber allows silencer 200 to achieve efficient noise attenuation using the smallest possible space. Silencer 200, and any similar noise attenuators utilizing the acoustic metamaterial sound absorber, may be made from any type of suitable material, such as, for example, plastic, metal, glass, cardboard or the like.

20 Fig. 9A shows a sample noise spectrum obtained from a hair dryer in which the main noise component begins at 630 Hz (nearly 98% of the energy is distributed in this range). As shown in Figs. 10-12, silencer 200 uses FP channels as the resonant structures. Based on the energy distribution of the original noise spectrum, as shown in Fig. 9A, silencer 200 is designed in a manner similar to that described above, with first portion 210 defining outlet

25 216, which forms a channel for the air flow from the hairdryer fan (not shown). Fig. 11 is a sectional view, illustrating the folded channels internal to first portion 210, as described above. In the sectional view of Fig. 11, each FP channel has one open end and one closed end. The openings of the channels connect directly to the ventilation area. It should be understood that the cross-sectional contour of the channels may have any suitable shape, such

30 as circular, rectangular, etc. Similarly, it should be understood that the channels may align in the circumferential direction, the radial direction, or in any other suitable direction.

By surrounding the fan, the second portion 212, as shown in Figs. 10 and 12, blocks noise leakage from the inlet 218. As shown in Figs. 10 and 13, the third portion 214 is a

ventilated plastic foam portion, where the inlet 218 is defined between the second portion 212 and the third portion 214. It should be understood that the overall structure of silencer 200 may be made from any suitable type of material, such as, for example, polylactide (PLA) plastic. Fig. 9B illustrates transmission loss when silencer 200 is used with the hairdryer of Fig. 9A. Specifically, Fig. 9B shows the transmission loss induced by first portion 210, with the experimental results being measured by a conventional impedance tube. It can be seen in Fig. 9B that the minimal transmission loss is about 10 dB above 630 Hz, which covers the main noise frequencies. Based on this transmission loss spectrum, the specific noise through first portion 210 has a sound pressure level drop from 75 dBA to 65 dBA. The solid curve in Fig. 9B was obtained by numerical simulations. It can be seen that the simulated results agree well with the measured results. By combining the first, second and third portions 210, 212, 214 to form the overall silencer 200, the overall sound pressure level shows a decrease from 75 dBA to 65 dBA, as measured by a sound level meter.

It is to be understood that the acoustic metamaterial sound absorber is not limited to the specific embodiments described above, but encompasses any and all embodiments within the scope of the generic language of the following claims enabled by the embodiments described herein, or otherwise shown in the drawings or described above in terms sufficient to enable one of ordinary skill in the art to make and use the claimed subject matter.

CLAIMS

1. An acoustic metamaterial sound absorber, comprising an array of acoustic resonance cavities, a density of number of modes per unit frequency, D , associated with the array of acoustic resonance cavities being given by $D = \frac{2}{\pi[\alpha(\Omega)Z(\Omega)]}$, where Ω is a resonant frequency of each mode associated with the array of acoustic resonance cavities, $\alpha(\Omega)$ is an oscillator strength at the resonant frequency Ω , and $Z(\Omega)$ is a target impedance.
2. The acoustic metamaterial sound absorber as recited in claim 1, further comprising a sound absorbing layer mounted on the array of acoustic resonance cavities.
3. The acoustic metamaterial sound absorber as recited in claim 2, wherein the sound absorbing layer is formed from a sound absorbing material selected from the group consisting of wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof.
4. The acoustic metamaterial sound absorber as recited in claim 1, wherein each of the acoustic resonance cavities is at least partially filled with a sound absorbing material.
5. The acoustic metamaterial sound absorber as recited in claim 4, wherein the sound absorbing material is selected from the group consisting of wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof.
6. The acoustic metamaterial sound absorber as recited in claim 1, wherein each of the acoustic resonance cavities comprises a Fabry-Pérot cavity.
7. The acoustic metamaterial sound absorber as recited in claim 1, wherein the array of acoustic resonance cavities has a minimum thickness, $d_{\min}$, defined by $d_{\min} = \frac{1}{4\pi^2} \frac{B_{\text{eff}}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|$, where λ is an acoustic wavelength in the air, $A(\lambda)$ is an absorption coefficient, B_{eff} is an effective bulk modulus of the array of acoustic resonance cavities in a static limit, and B_0 is a bulk modulus of the air.
8. The acoustic metamaterial sound absorber as recited in claim 1, wherein each of the acoustic resonance cavities is folded to have at least one inlet, an opposed closed end and at least two plies.
9. An acoustic metamaterial sound absorber, comprising an array of acoustic resonance cavities having a minimum thickness, $d_{\min}$, defined by $d_{\min} = \frac{1}{4\pi^2} \frac{B_{\text{eff}}}{B_0} \left| \int_0^\infty \ln[1 - A(\lambda)] d\lambda \right|$, where λ is an acoustic wavelength in air, $A(\lambda)$ is an absorption coefficient, B_{eff} is an effective bulk modulus of the array of acoustic resonance cavities in a static limit, and B_0 is a bulk modulus of the air.

10. The acoustic metamaterial sound absorber as recited in claim 9, further comprising a sound absorbing layer mounted on the array of acoustic resonance cavities.

11. The acoustic metamaterial sound absorber as recited in claim 10, wherein the sound absorbing layer is formed from a sound absorbing material selected from the group consisting of wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof.

12. The acoustic metamaterial sound absorber as recited in claim 9, wherein each of the acoustic resonance cavities is at least partially filled with a sound absorbing material.

13. The acoustic metamaterial sound absorber as recited in claim 12, wherein the sound absorbing material is selected from the group consisting of wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof.

14. The acoustic metamaterial sound absorber as recited in claim 9, wherein each of the acoustic resonance cavities comprises a Fabry-Pérot cavity.

15. The acoustic metamaterial sound absorber as recited in claim 9, wherein a density of number of modes per unit frequency, D , associated with the array of acoustic resonance cavities is given by $D = \frac{2}{\pi[\alpha(\Omega)Z(\Omega)]}$, where Ω is a resonant frequency of each mode associated with the array of acoustic resonance cavities, $\alpha(\Omega)$ is an oscillator strength at the resonant frequency Ω , and $Z(\Omega)$ is a target impedance.

16. The acoustic metamaterial sound absorber as recited in claim 9, wherein each of the acoustic resonance cavities is folded to have at least one inlet, an opposed closed end and at least two plies.

17. An acoustic metamaterial sound absorber, comprising:

a first array of acoustic resonance cavities, wherein each of the acoustic resonance cavities of the first array of acoustic resonance cavities extends linearly and has an inlet and an outlet;

25 a second array of acoustic resonance cavities, wherein each of the acoustic resonance cavities of the second array of acoustic resonance cavities is folded to have at least one inlet, an opposed closed end and at least two plies; and

a third array of acoustic resonance cavities, wherein each of the acoustic resonance cavities of the third array of acoustic resonance cavities is folded to have at least one inlet, an opposed closed end and at least three plies, the second array of acoustic resonance cavities being sandwiched between the first array of acoustic resonance cavities and the third array of acoustic resonance cavities.

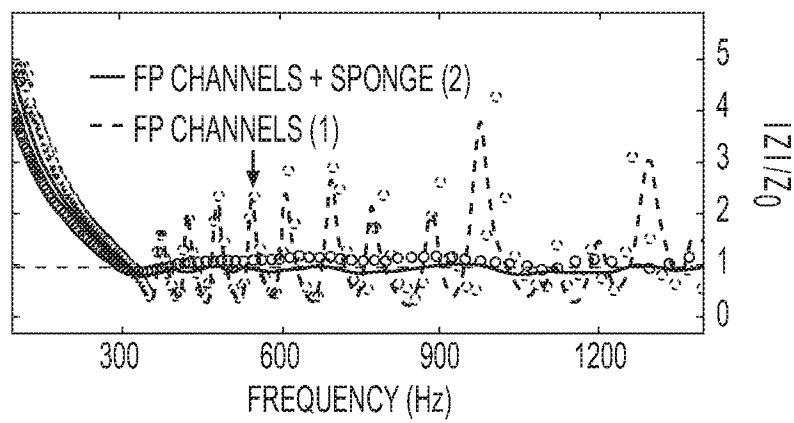
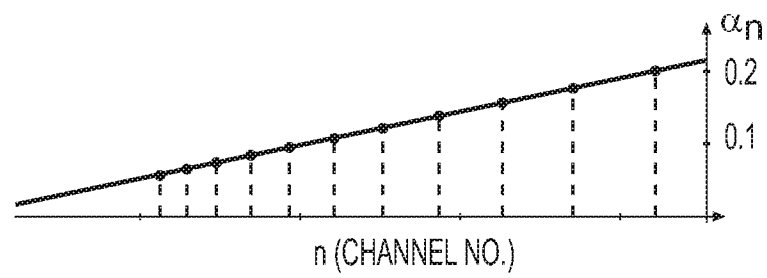
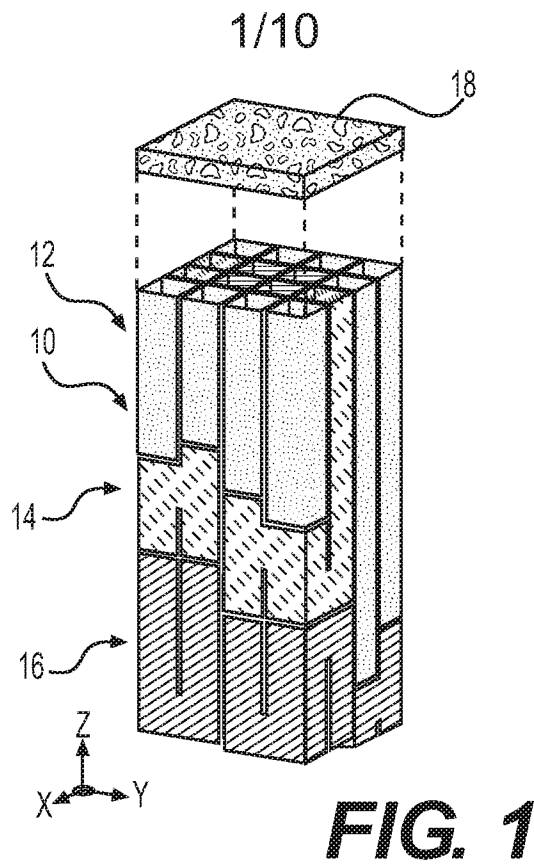
18. The acoustic metamaterial sound absorber as recited in claim 17, further comprising a sound absorbing layer mounted on the first array of acoustic resonance cavities to cover the inlet of each of the acoustic resonance cavities of the first array of acoustic resonance cavities.

5 19. The acoustic metamaterial sound absorber as recited in claim 18, wherein each of the acoustic resonance cavities of the first array of acoustic resonance cavities extends linearly along a transverse axis, the acoustic resonance cavities of the first array of acoustic resonance cavities being arrayed in a square grid-wise pattern along a lateral axis and a longitudinal axis, wherein the transverse, lateral and longitudinal axes are mutually
10 orthogonal with respect to one another.

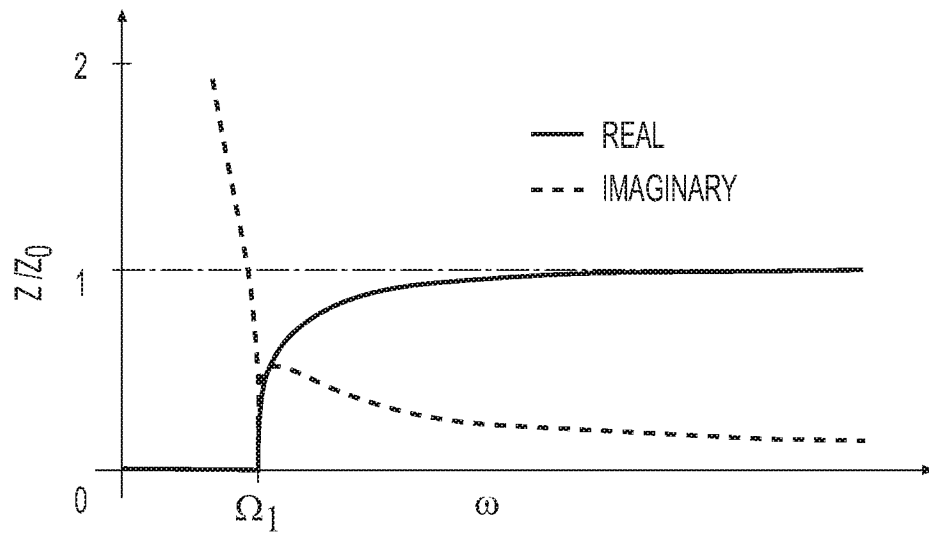
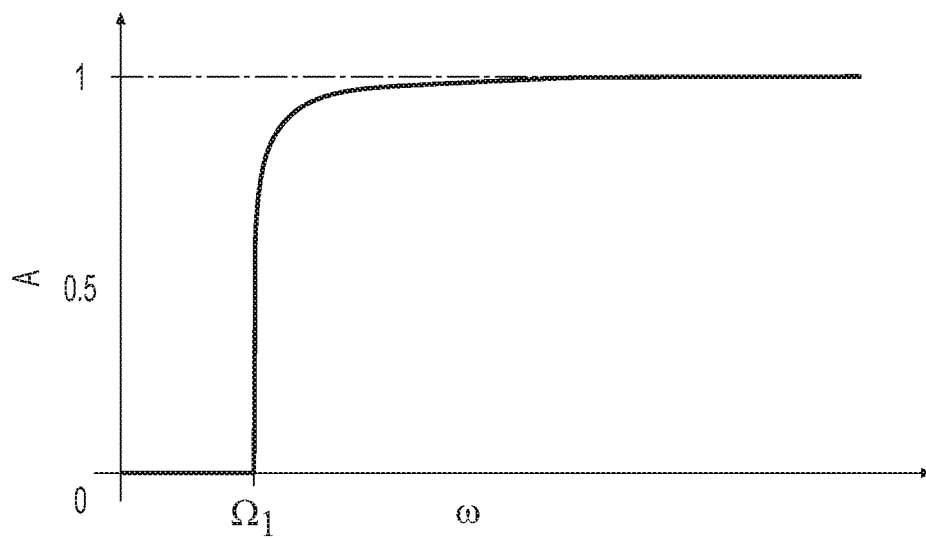
20. The acoustic metamaterial sound absorber as recited in claim 19, wherein the sound absorbing layer is formed from a sound absorbing material selected from the group consisting of wool, sponge, fiber, cotton, metallic weave, cloth and combinations thereof.

21. The acoustic metamaterial sound absorber as recited in claim 20, wherein each of
15 the acoustic resonance cavities of the first array of acoustic resonance cavities comprises a Fabry-Pérot cavity.

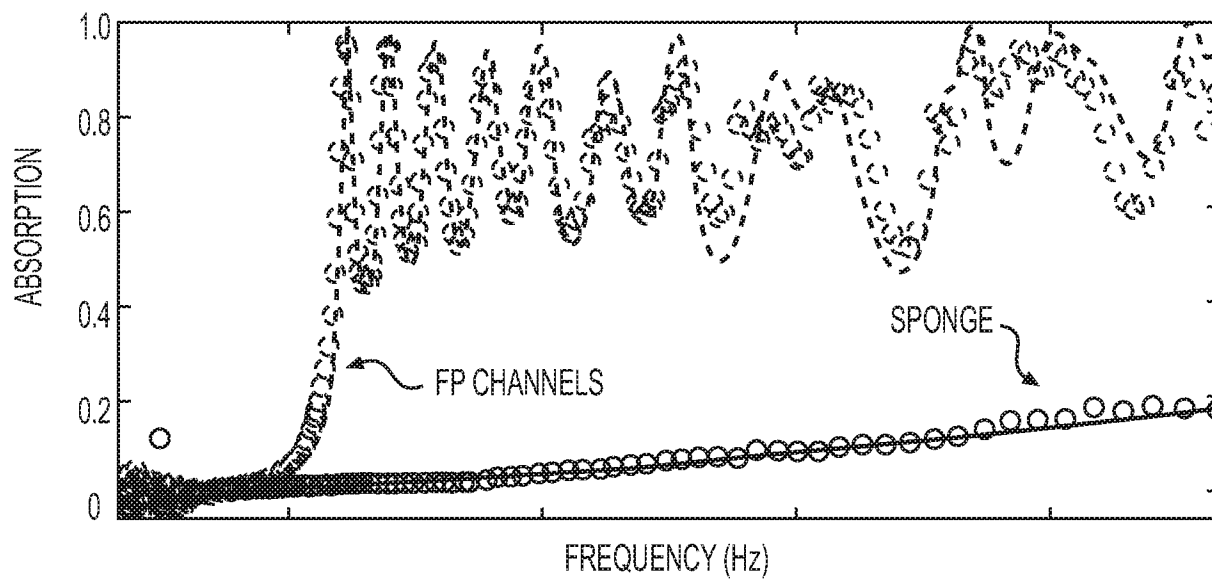
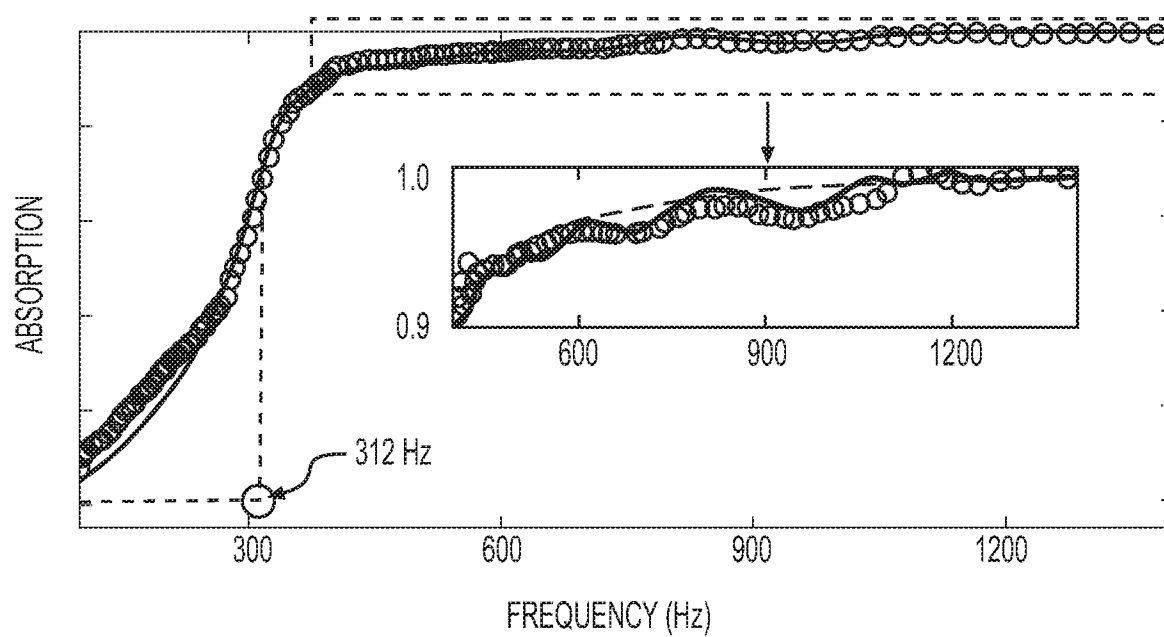
22. The acoustic metamaterial sound absorber as recited in claim 21, wherein each of the acoustic resonance cavities of the second and third arrays of acoustic resonance cavities comprises a Fabry-Pérot cavity.



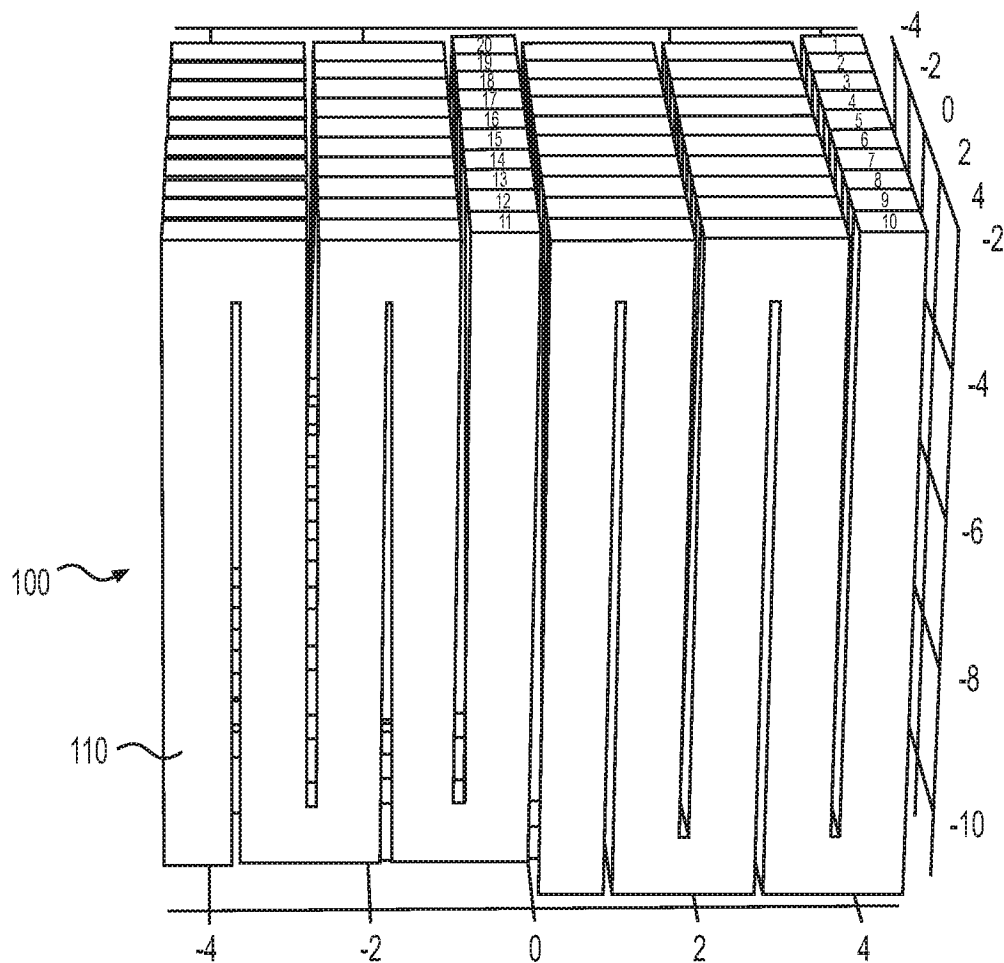
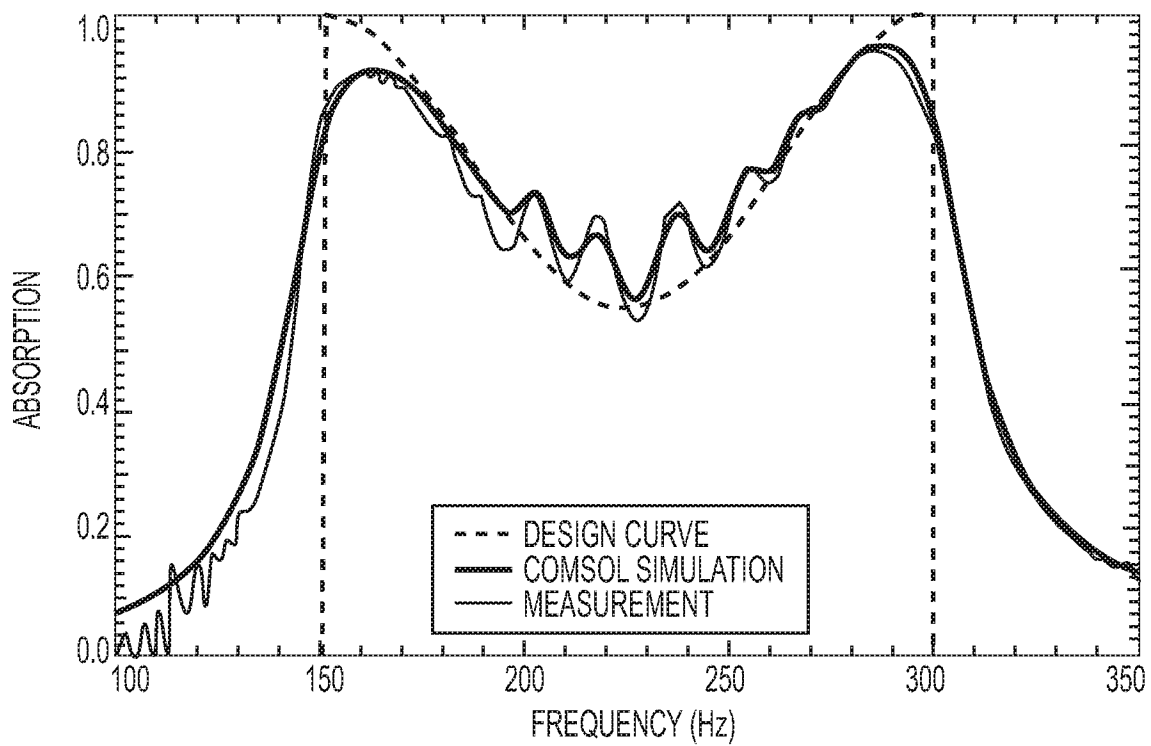
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**FIG. 4****FIG. 5**

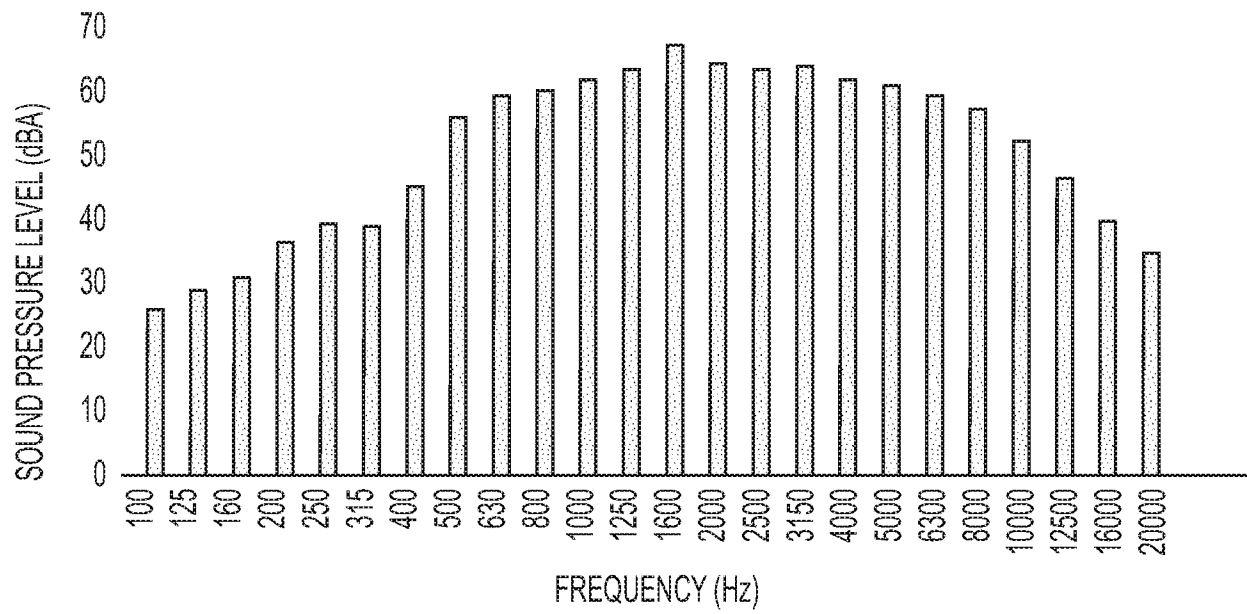
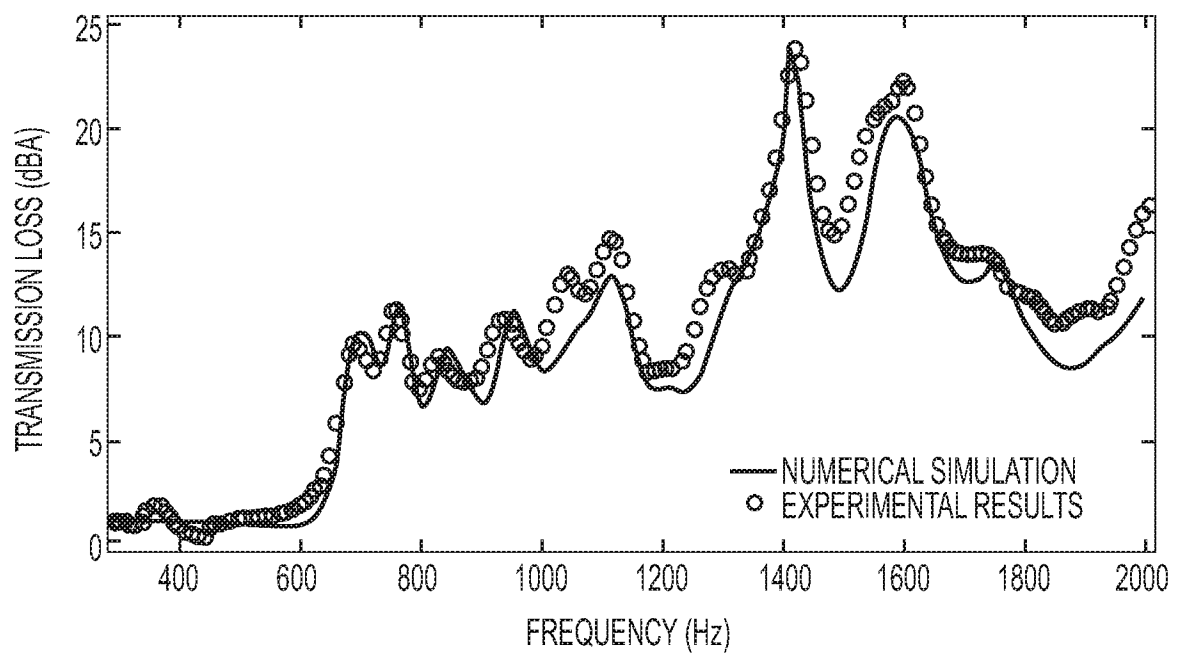
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**FIG. 6A****FIG. 6B**

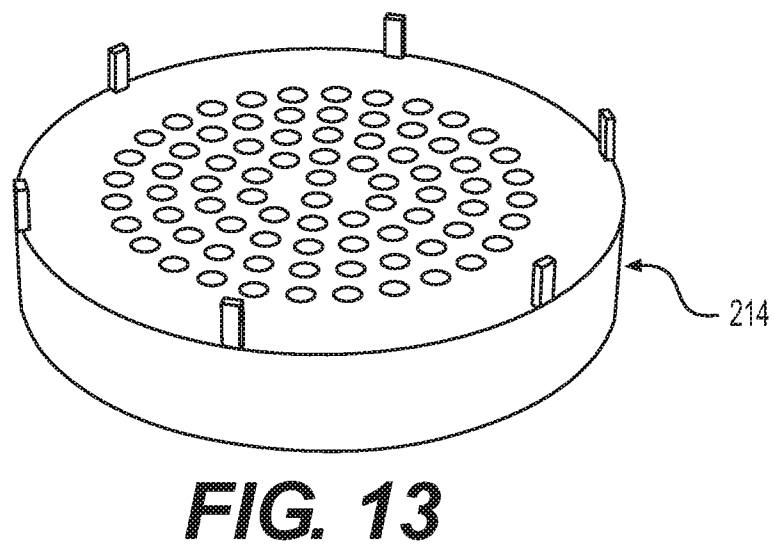
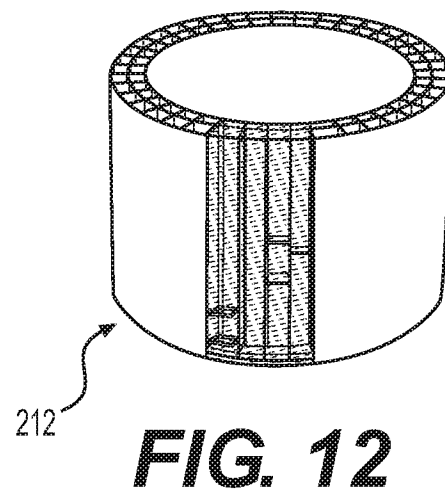
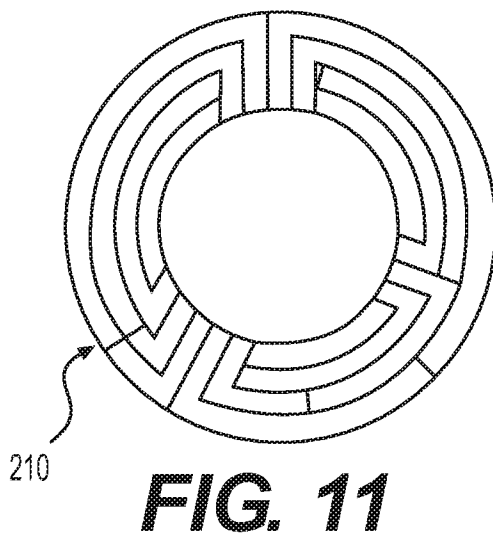
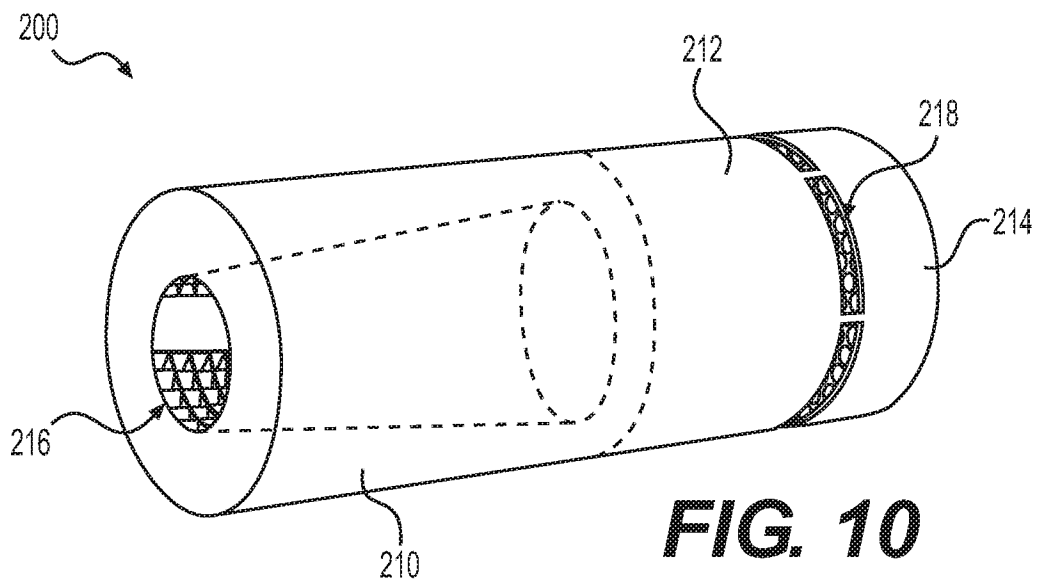
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**FIG. 7****FIG. 8**

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**FIG. 9A****FIG. 9B**

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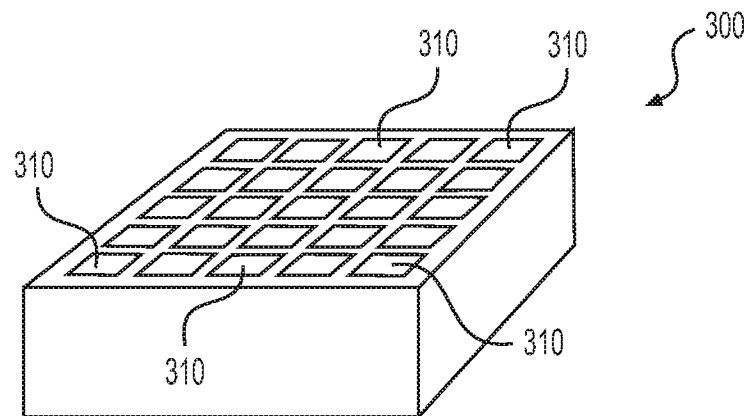


FIG. 14

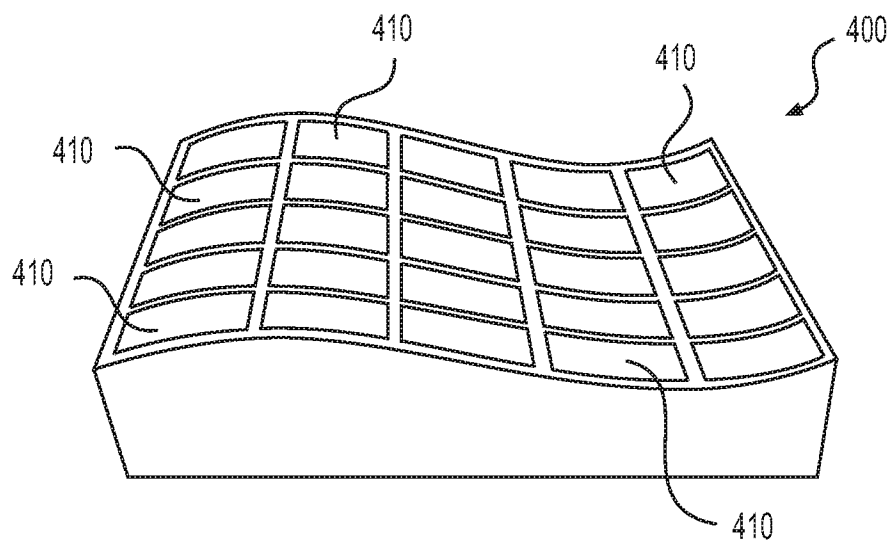


FIG. 15

8/10

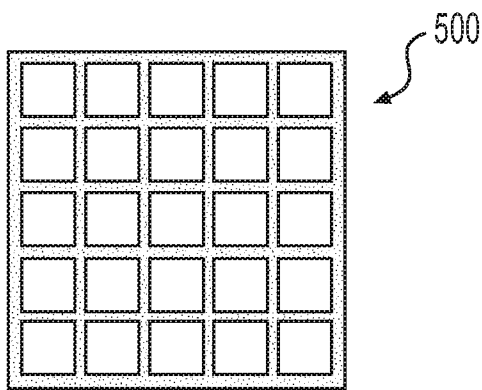


FIG. 16A

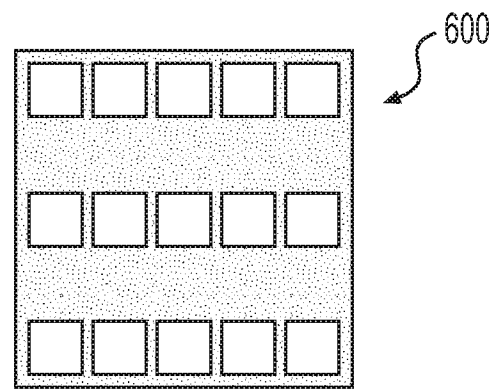


FIG. 16B

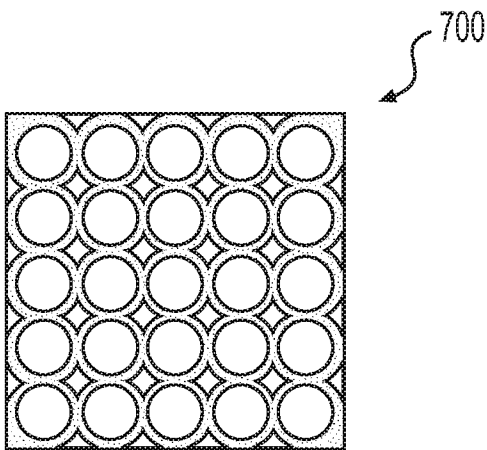


FIG. 16C

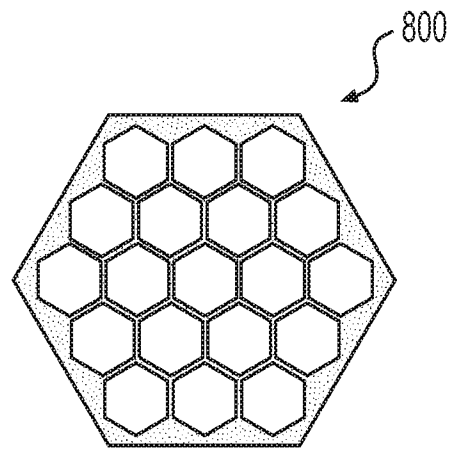


FIG. 16D

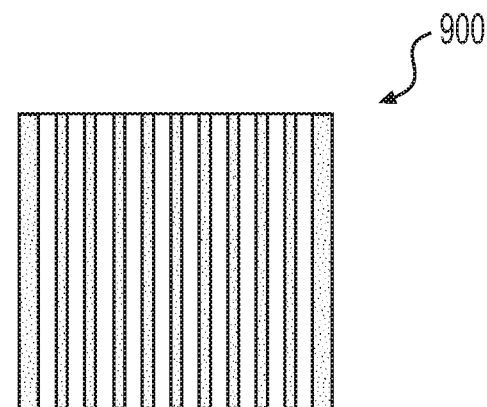


FIG. 16E

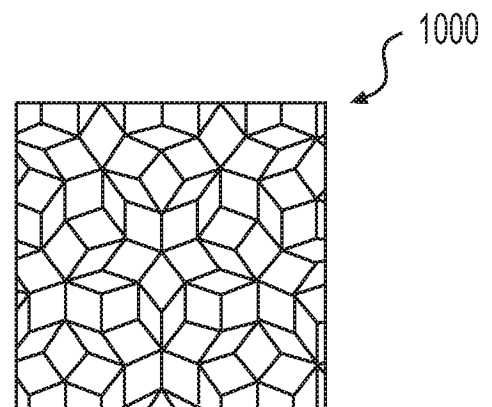


FIG. 16F

1100

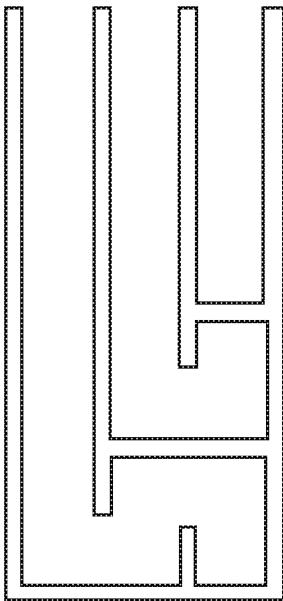


FIG. 17A

1200

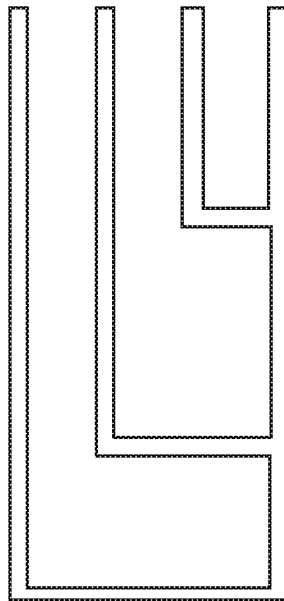


FIG. 17B

1300

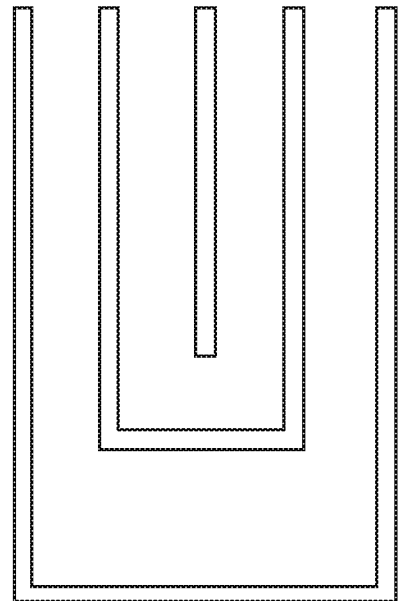


FIG. 17C

10/10

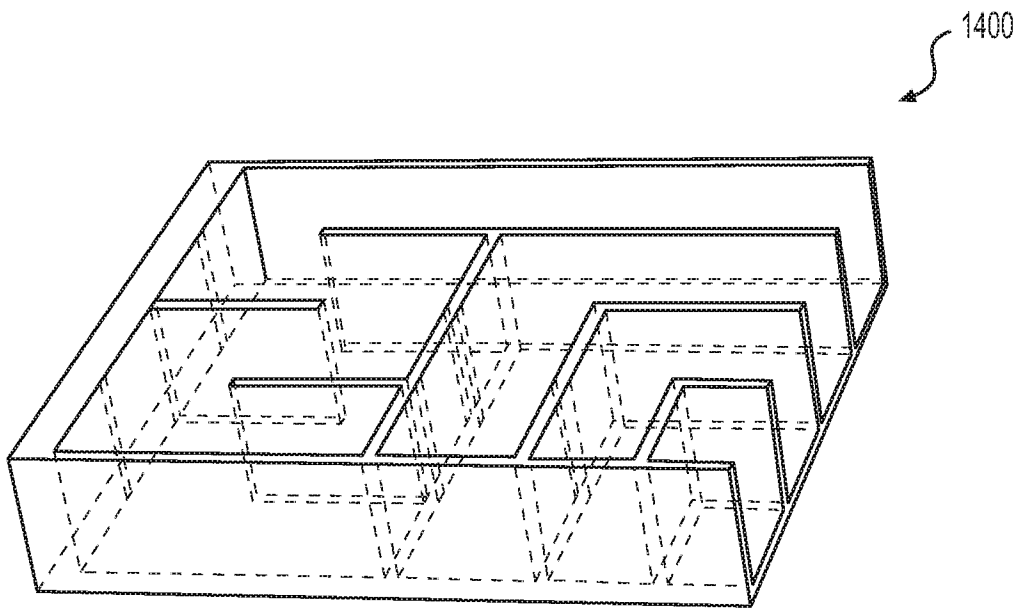


FIG. 18

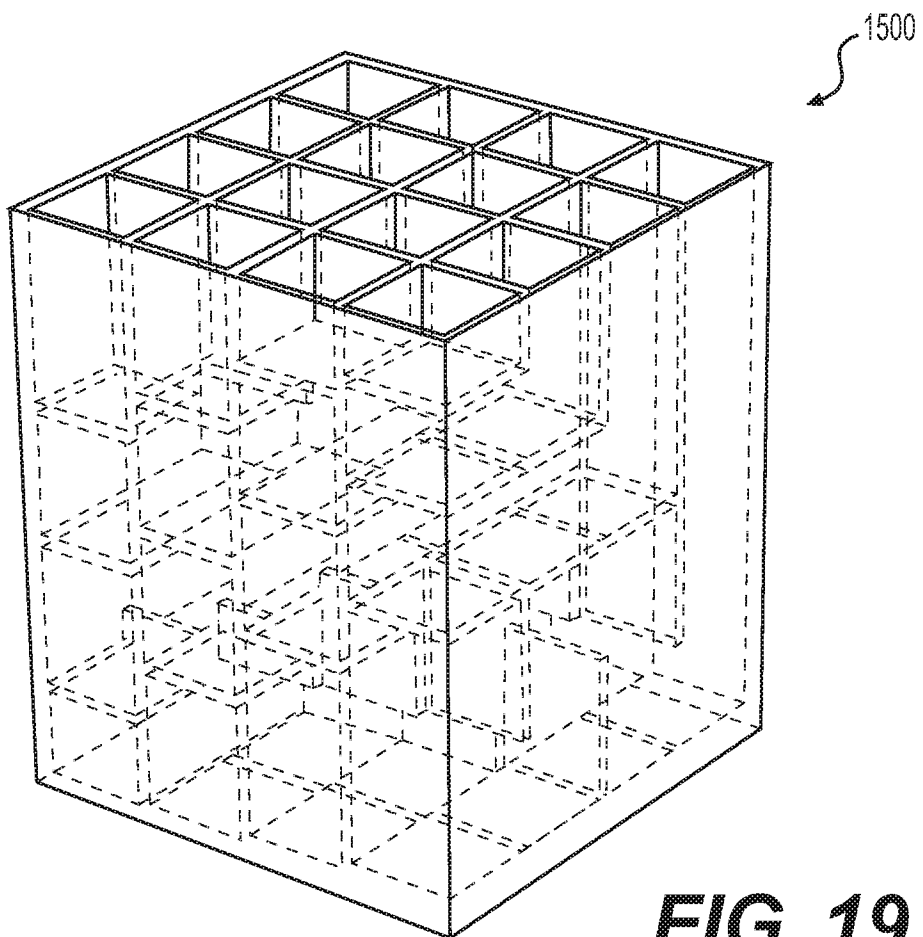


FIG. 19

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2017/057076

A. CLASSIFICATION OF SUBJECT MATTER

G10K 11/16(2006.01)i; E04B 1/86(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/-; E04B1/-

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, CNPAT, CNKI: ACOUSTIC, METAMATERIALS, YANG Ming, Chen Shuyu, Fu Caixing, Xiao Songwen, Sheng Ping, sound, absor+, more, many, multi, two, double, three, triple, array, resona+, cavit+, room, frequenc+, oscillat+, strength, impedance, resistance, thickness, wavelength, fold+

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 101727894 A (INSTITUTE OF ACOUSTIC, CHINESE ACADEMY OF SCIENCES) 09 June 2010 (2010-06-09) see description, paragraphs [0042]-[0078] and figures 1-15	1-22
A	CN 1317629 A (ISUZU MOTORS LTD.) 17 October 2001 (2001-10-17) the whole document	1-22
A	CN 103178279 A (SAMSUNG ELECTRONICS CO., LTD.) 26 June 2013 (2013-06-26) the whole document	1-22
A	CN 103249941 A (WEBASTO AG.) 14 August 2013 (2013-08-14) the whole document	1-22
A	CN 2830654 Y (CHEN, KEN) 25 October 2006 (2006-10-25) the whole document	1-22
A	US 2006050346 A1 (SAMSUNG ELECTRONICS CO., LTD.) 09 March 2006 (2006-03-09) the whole document	1-22

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

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“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

06 February 2018

Date of mailing of the international search report

24 February 2018

Name and mailing address of the ISA/CN

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Telephone No. (86-10)53962642

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/IB2017/057076

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				WO	2012055900	A1	03 May 2012
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				DE	102010049578	A1	26 April 2012
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				US	2013327584	A1	12 December 2013
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US	2006050346	A1	09 March 2006	KR	100693037	B1	12 March 2007
				KR	20060020515	A	06 March 2006