# Phononics 2013

## 2nd International Conference on Phononic Crystals/ Metamaterials, Phonon Transport & Optomechanics

**June 2-7, 2013 – Sharm El-Sheikh, Egypt**

*2013 Brillouin Medal Recipients:*

*Ping Sheng*
*Che Ting Chan*
*Zhiyu Yang*

*Department of Physics,*
*The Hong Kong University of Science and Technology*
*Hong Kong*

Léon Brillouin (1889-1969)

# Brillouin Medal

The Brillouin Medal honors the renowned French physicist, Léon Brillouin, who among many contributions to quantum mechanics and condensed matter physics has discovered the concept of the *Brillouin zones*. His discovery has laid the foundation for a rigorous mathematical treatment of wave motion in the reciprocal lattice space, and has since been applied to all problems that involve wave propagation in a periodic medium.  Brillouin is also known for the development of the BWK method of approximating solutions to the Schrödinger equation in 1926. Léon Brillouin was born in Sèvres, near Paris, in 1889. Brillouin studied physics at the École Normale Supérieure in Paris from 1908 to 1912. He was professor at the Sorbonne (1928), and subsequently professor at the College de France (1932-1949). During the war, Léon Brillouin emigrated to the United States, where he became a professor at the University of Wisconsin (1941) and Harvard (1946). He received the US citizenship in 1949. From 1948-53, he was Director of Electronic Education at IBM, and from 1953 until his death in 1969, he was a professor at Columbia University in New York City. In 1953, Professor Brillouin was elected a member of the National Academy of Sciences.

At Phononics 2013, the *Brillouin Medal* is being inaugurated to "honor a specific seminal contribution, as presented by up to three related publications, by a single researcher or up to three researchers working in collaboration, in the field of phononics (including phononic crystals, acoustic/elastic metamaterials, nanoscale phonon transport, wave propagation in periodic structures, coupled phenomena involving phonons, and related areas)". The medal is awarded biennially at the time of the Phononics 20xx conference. The recipient(s) deliver the *Brillouin Lecture* at the conference, and is (are) also invited to write a 6-page *Brillouin Paper* to be published alongside the conference proceedings.

The 2013 Brillouin Medal is awarded to Professor **Ping Sheng**, Professor **Che Ting Chan** and Professor **Zhiyu Yang** for their discovery of the concept of a "locally resonant acoustic metamaterial" and related contributions.

## *2013 Brillouin Medal Committee**

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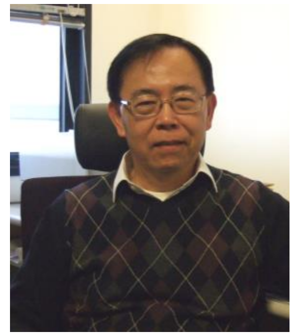
# Ping Sheng



William Mong Professor of Nanoscience

Chair Professor of Physics

Department of Physics

Hong Kong University of Science and Technology (HKUST)

### Biographical Sketch

Ping Sheng is the William Mong Professor of Nanoscience and Chair Professor of Physics at the Hong Kong University of Science and Technology. He obtained his BSc in Physics from the California Institute of Technology and PhD in Physics from Princeton University in 1971. After a stay at the Institute for Advanced Study, Ping joined RCA David Sarnoff Research Center in 1973 as a member of technical staff. In 1979 he joined the Exxon Corporate Research Lab, where he served as the head of the theory group from 1982-86. In 1994 Ping joined the HKUST as a professor of physics and served as the head of the physics department from 1999 to 2008.

Professor Ping is a Fellow of the American Physical Society and a Member of the Asia Pacific Academy of Materials. He is also a member of the editorial boards of New Journal of Physics and Solid State Communications. In 2002, he was awarded Technology Leader of the Year by the Sing Tao Group.

Professor Ping has published more than 430 papers with a total of over 16,000 citations. He has presented over 290 keynote or invited talks at international meetings and conferences. His current research interests include acoustic metamaterials, superconductivity in carbon nanotubes, giant electrorheological fluids, and fluid-solid interfacial phenomena.

# Che Ting Chan

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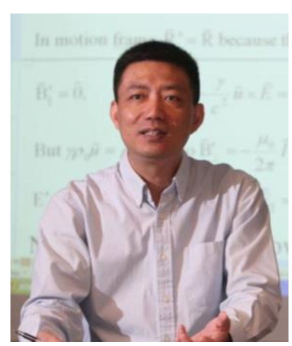
### Biographical Sketch

Che Ting Chan received his BSc degree from the University of Hong Kong in 1980 and his PhD degree from the University of California at Berkeley in 1985. He is currently a Chair Professor of Physics at HKUST and the Executive Director of HKUST Institute for Advanced Study. He has been elected a Fellow of the American Physical Society since 1996. He received the Achievement in Asia Award of the Overseas Chinese Physics Association (2000) and Croucher Senior Research Fellowship (2010). His primary research interest is the simulation of material properties. He is now working on the theory of a variety of advanced materials, including photonic crystals, metamaterials and nano-materials.

# Zhiyu Yang



Professor of Physics

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### Biographical Sketch

Zhiyu Yang received his BSc degree from Fudan University in 1983 and his PhD degree from Purdue University in 1988. He is currently a Professor of Physics at HKUST. His primary research interest is experimental investigation and application of phononic metamaterials. He is now working on a variety of membrane-type phononic metamaterials, including doubly negative metamaterials, super absorptive metamaterials, and high damping metamaterials.

# Acoustic Metamaterials

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**Abstract:** We present the basic concept of acoustic metamaterials and their initial realization in the form of locally resonant sonic materials. The development of acoustic metamaterials has led to the realization of many acoustic and elastic functionalities previously thought to be not possible, such as acoustic cloaking and the attenuation of sound in the 100 to 1000 Hz range by using thin membranes.

## I. Introduction

The advent of photonic and phononic crystals, beginning in the 1980s, was at least partially propelled by analogy to electrons' wave characteristics in crystalline semiconductors. However, it is well known in solid state physics that there are two complementary ways to look at band and bandgap formation in electronic crystals. One is Bragg scattering, which relies on crystal periodicity. This is the basic mechanism utilized by photonic and phononic crystals. The other is the tight-binding approach, in which the discrete electronic energy levels of the atoms are broadened into bands when they come close to each other and interact through the overlap of electronic wavefunctions. Bandgaps are the remnants of the discrete energy level separations when the neighboring bands do not completely overlap. Acoustic metamaterials' underlying concept is based on this second perspective.

Basic to the tight binding approach is that the atoms should have discrete levels that are the consequence of atoms' internal structure. For acoustic metamaterials, it means that the basic constituents should possess local resonances. Here the term "local resonance" is meant to distinguish it from structural resonances that are common to all elastic systems. The initial realization[1] of such a unit consists of metallic spheres, 1 cm in diameter, each wrapped in a thin layer of silicone rubber, shown in Fig. 1(A). Such a unit has two resonances when it is embedded in a relatively rigid matrix. Oscillation of the metallic sphere, with the silicone rubber being the "spring," constitutes the lower frequency resonance. The higher frequency resonance is dominated by the vibration of the silicone rubber coating, with relatively small movement of the metallic sphere. In Fig. 1(B) we show the units glued together into a cubic lattice by using epoxy.

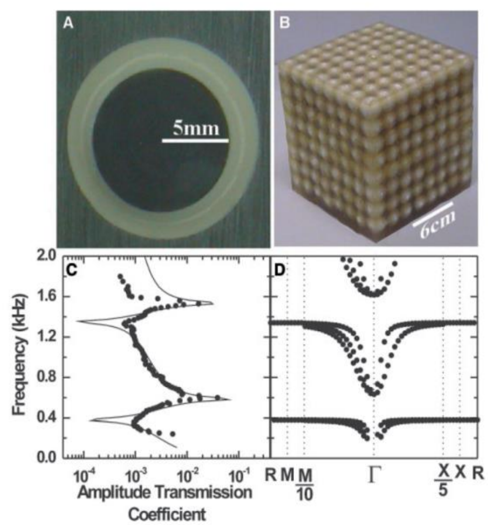


**Figure 1** (A) Cross section of a coated sphere that forms the basic structure unit (B) for an 8x8x8 sonic crystal. (C) Calculated (solid line) and measured (circles) amplitude transmission coefficient along the [100] direction are plotted as a function of frequency. The calculation is for a four-layer slab of simple cubic arrangement of coated spheres, periodic parallel to the slab. The observed transmission characteristics correspond well with the calculated band structure (D), from 200 to 2000 Hz, of a simple cubic structure of coated spheres. Adapted from Ref. 1.

Such a material has interesting characteristics. First of all, the resonance frequencies are relatively low since the metallic sphere is heavy and the silicone rubber constitutes a weak spring; they are noted to be completely independent of the lattice constant of the cubic lattice. Second, no periodicity is required for the functionality of this material.

This is because of the local character of the resonances. In fact, the existence of bandgaps in amorphous tetrahedrally-coordinated solids was shown previously[2]. In general, bandgaps can arise from short-range order/structure (i.e., the form factor part of scattering from solids) just as well as from long-range periodicity (i.e., from the structure factor part of the scattering from solids).

## II. Negative effective dynamic mass density

In the case of locally resonant sonic materials[1], the low frequency bandgaps can be attributed to negative effective material parameter arising from the resonances. And in this case it is due to the negative value of the dynamic mass density[3], defined as

$$D_{eff} = \langle f \rangle / \langle a \rangle , \tag{1}$$

where $\langle f \rangle$ denotes the spatially averaged force density and $\langle a \rangle$ the averaged acceleration. Since the sound velocity is given by $v = \sqrt{B_{eff} / D_{eff}}$, with $B_{eff}$ denoting effective bulk modulus, a negative mass density implies evanescent waves for the frequency regime over which this is the case. The definition of effective dynamic mass density, Eq. (1), is noted to differ from the static mass density of a composite, given by $\rho_{eff} = \phi\rho_1 + (1-\phi)\rho_2$ for a two-component composite. Physically this difference arises from the relative motions between the different components. Whereas the arithmetic averaging of the mass densities implies motions in unison, the relative motion between the components, which can be amplified in the case of local resonances, can imply values of $D_{eff}$ that is complex or even negative. Hence in Figs. 1(C) and 1(D) we can see that the low frequency gap exists between the transmission dip and transmission peak. This is precisely the regime over which the dynamic mass density is negative (see below).

The transmission dip seen in Fig. 1(C) is easily verified to break the so-called mass density law that holds for the transmission $T$ of air-borne sound through a solid wall[1] of mass density $\rho$ and thickness $d$ that is much less than the relevant sound wavelength $\lambda$:

$$T \propto (\omega\rho d)^{-1} . \tag{2}$$

It is noted that in Eq. (2) the bulk modulus of the solid wall does not play a role; that is why it is denoted the mass density law. The transmission dip shown in Fig. 1(C) is due to near-total reflection of the low frequency sound, since the absorption has been measured to be small. What is more significant, however, is the different addition rule implied by the locally resonant sonic material. That is, if we double the thickness $d$ of the wall, the mass density law predicts a ~6 dB additional attenuation. However, for the locally resonant sonic materials the doubling of thickness implies a multiplicative effect. Hence if the original sample has 18 dB intrinsic attenuation, then a two-layer sample would mean a 36 dB attenuation.

## III. Development of acoustic meta-functionalities

Elastic constants play an equally important role as the mass density in determining a material's response to elastic/acoustic waves. In the context of elasticity, bulk modulus describes the elastic deformation that leads to a change in volume. The realization of negative dynamic mass density makes obvious that another hallmark should be the realization of double negativity in which both bulk modulus and effective mass are negative. That would lead to a "left handed" material[4]. The existence of such acoustic metamaterial was first proposed and demonstrated through simulations in 2004[5]. Negativity in bulk modulus means that the medium expands under compression and contracts upon release. Thermodynamics dictates that a system with such a static response characteristic must be unstable. However, negative bulk modulus is possible in the context of dynamic response of an elastic/acoustic system, whereby the material display an out-of-phase response to an AC pressure field. Experimentally, negative effective bulk modulus was first realized by the Berkeley group[6]. The structure consists of a fluid channel that is sideway shunted by a series of periodically placed Helmholtz resonators (HRs). Instead of utilizing combinations of several materials, this metamaterial system seeks to produce modulus-type response by shaping the geometry that confines fluid in which sound propagates.

The realization of negative mass density and elastic bulk modulus sets the stage for new acoustic meta-functionalities, aided by the tool of transformation optics/acoustics. In electromagnetic waves, amazing wave manipulation devices such as invisibility cloaks have been realized using the new paradigm of transformation optics which is based on the covariance property of the Maxwell equations upon coordinate transformation[7]. It turns out that we can build transformation acoustics on the same footing. Let us consider the time harmonic acoustic equation $\nabla\cdot[\vec{\rho}(x)^{-1}\nabla p(x)] = -[\omega^2/\kappa(x)]p(x)$, where $\omega$ is frequency, $p(x)$ and $\kappa(x)$ are the pressure and bulk modulus distribution and $\vec{\rho}(x)$ is the mass density tensor. If we apply a coordinate transformation $x'(x)$ to map each point $x$ to a corresponding point $x'(x)$ in another space, the acoustic equation in the new space has the same form $\nabla'\cdot[\vec{\rho}\,'(x')^{-1}\nabla' p'(x')] = -[\omega^2/\kappa'(x')]p'(x')$, with the constitutive parameters transforming as $\kappa'(x') = \det A \times \kappa(x)$ and $\vec{\rho}\,'(x')^{-1} = A[\vec{\rho}(x)^{-1}]A^T/\det A$. Here $A$ is the Jacobian matrix of coordinate transformation. This equation relates the acoustic parameters of the transformed acoustic material to a coordinate transformation, and gives us the recipe to design materials that can bend acoustic waves in almost any way we desire by changing the coordinate systems[8-10].

A mapping that can produce acoustic cloaking in a 3D spherical geometry is the "radial push forward mapping"[11,12] which expands a point into a sphere (a circle in 2D) and can be written as $r = f(r'), \theta' = \theta, \varphi' = \varphi,$ with

$$f(r') = \begin{cases} r', & r' \geq b, \\ b(r'-a)/(b-a(\quad)), & a \leq r' < b, \end{cases} \tag{3}$$

where $a$ and $b$ are the inner and outer radii of the cloaking shell and the resulting effective density and the modulus in the spherical acoustic cloaking shell have the form

$$\begin{aligned} \rho_r &= \rho_0 \frac{b-a}{b}\left(\frac{r'}{r'-a}\right)^2, \\ \rho_\theta &= \rho_\varphi = \rho_0 \frac{b-a}{b}, \\ \kappa'(r',\theta',\varphi') &= \kappa_0\left(\frac{b-a}{b}\right)^3\left(\frac{r'}{r'-a}\right)^2. \end{aligned} \tag{4}$$

These constitutive parameters are inhomogeneous and can attain extreme values. Moreover, the effective dynamic density is anisotropic. It is clear that such materials do not exist in nature and the achievement of acoustic cloaking in some specific frequency hinges on the availability of acoustic metamaterials that can realize nearly arbitrary values of effective density and modulus tensors, owing to their resonant behavior. Acoustic cloaking has indeed been experimentally realized[13,14].

Other acoustic meta-functionalities have also recently been realized or pursued. Acoustic focusing and superlensing[15-25] were pursued theoretically and experimentally. An acoustic hyperlens was experimentally demonstrated[26]. Acoustic rectification[27] and unidirectional acoustic diode[28], were also recently experimentally realized. Hybrid elastic solid that can behave as liquid within a certain frequency range[29] was shown to be possible, and the fact that the dynamic mass density can differ from the static mass density was also generalized to the low frequency regime[30] for the fluid-solid composites.

## IV. Membrane-type acoustic metamaterials

The functionality at subwavelength scale is one of the most important characteristics for acoustic metamaterials; hence its use in low frequency acoustics would be most promising, since low frequency sound is known for its difficulty to be attenuated and manipulated. The early version of resonant sonic materials is still bulky. Hence ideally one should have a membrane-type acoustic metamaterial which can both reflect and/or absorb sound in the 100-1000 Hz regime. The realization of such "2D" acoustic metamaterials[31] can also open the door to broad-band applications through stacking the membranes that are operative in non-overlapping frequency regimes.

There is an intuitive dilemma encountered in attempting to reflect low frequency sound by using membrane samples, shown in Fig. 2. That is because total reflection of air-borne sound from a solid surface implies that the solid surface acts as a node of the wave, i.e., the solid surface has no displacement. However, for a soft membrane in the presence of an incident low frequency pressure wave, that seems intuitively very unlikely.

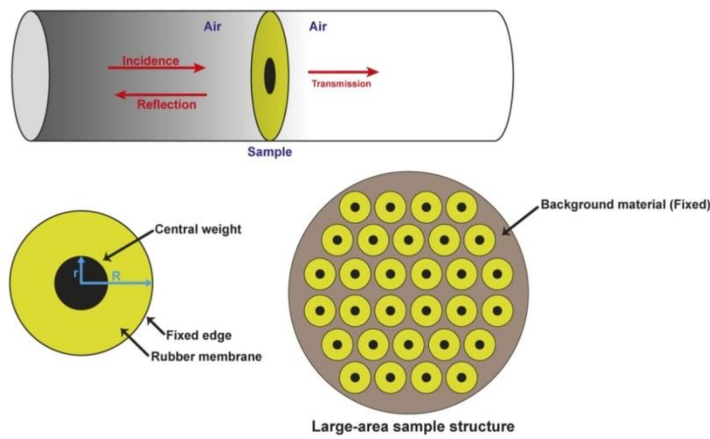


**Figure 2** Typical sample structure of the membrane-type acoustic metamaterial (bottom panels) and the testing geometry (upper panel). Adapted from Ref. 32.

By decorating the soft membrane (using the same material as that for the surgical glove) with a light button whose weight can be adjusted, we have realized the 2D version of the locally resonant sonic materials. There are naturally two resonances in the low frequency regime, just as in the 3D case, and between the two resonances there is always a frequency at which not only are the two resonances simultaneously excited with the opposite phase, but more importantly, the averaged normal displacement $\langle w \rangle$ of the decorated membrane is zero. This is the anti-resonance condition, because at this frequency the membrane is totally de-coupled from the radiating modes as can be seen as follows.

For acoustic wave in air, $k_{\parallel}^2 + k_{\perp}^2 = \omega^2 / v^2 = (2\pi/\lambda)^2$, where $\vec{k}_{\parallel}$, $k_{\perp}$ denote the wave vector components parallel or perpendicular to the surface of the membrane, respectively, $v$ = 340 m/s is the speed of sound in air, and $\lambda$ is the wavelength. At the air-membrane interface, we note that the normal displacement (which is usually sub-micron in magnitude and hence small compared to the membrane thickness) pattern of the membrane can be fully described by using two dimensional Fourier components of $\vec{k}_{\parallel}$. If we decompose the normal displacement $w$ into an area-averaged component plus another component of whatever is leftover, i.e., $w = \langle w \rangle + \delta w$, then it should be clear that their respective Fourier components' magnitudes must have a distribution, with the $\delta w$ part of the displacement having the overwhelming majority of the $\vec{k}_{\parallel}$ components with magnitudes $|k_{\parallel}| \geq 2\pi/d >> 2\pi/\lambda$. Hence from the dispersion relation it follows that the associated $k_{\perp}^2 < 0$. That is, the $\delta w$ part of the displacement can only cause evanescent waves. In contrast, for the $\langle w \rangle$ part of the normal displacement the distribution of the $|k_{\parallel}|$ must be peaked at zero, owing to its piston-like motion. Thus from the dispersion relation the associated $k_{\perp}^2 \sim (2\pi/\lambda)^2$. It follows that only the average component of the normal displacement can effect far-field transmission. If $\langle w \rangle = 0$, then there can be no far-field transmission.

The anti-resonance condition is easily shown to be the manifestation of the dynamic mass density dispersion, because

$$D_{eff} = -\langle \sigma_{zz} \rangle / \left( h \langle a_z \rangle \right) = \langle \sigma_{zz} \rangle / \left( -\omega^2 h \langle w \rangle \right), \tag{5}$$

where $\sigma_{zz}$ denotes the normal stress, and $h$ the membrane thickness. It is seen that when $\langle w \rangle = 0$, the $D_{eff}$ displays the behaviour shown in Fig. 3. In the same figure we also plot the measured transmission. If we use the dynamic mass density instead of the static mass density in the mass density law (Eq. (2)), then its validity seems to be recovered.

In looking back to the 3D version, where the anti-resonance condition also holds, the first transmission dip frequency is seen to occur below that of the transmission peak, so that the bandgap is indeed due to the negative mass density value. Also, in Fig. 3, $D_{eff}$ is negative with a decreasing trend (towards negative infinity) as the frequency approaches zero. This would seem to contradict the common intuition that $D_{eff}$ should reduce to the volume-average value in the static limit. The fact that it does not do so in the present case is due to first, the assumption that the boundary of the membrane is fixed, so that in the long wavelength limit the membrane essentially transfers its load onto the fixed boundary. That means the fixed boundary can also be interpreted as a piece of very heavy mass. Second, the negative sign of $D_{eff}$, signifying off-phase response to the external force, is a reflection of Newton's 3rd law—the reaction is opposite to the applied force. Such behavior of $D_{eff}$ has also been referred to as the "Drude-type negative mass density" in analogy to free electrons in metal[33,34].

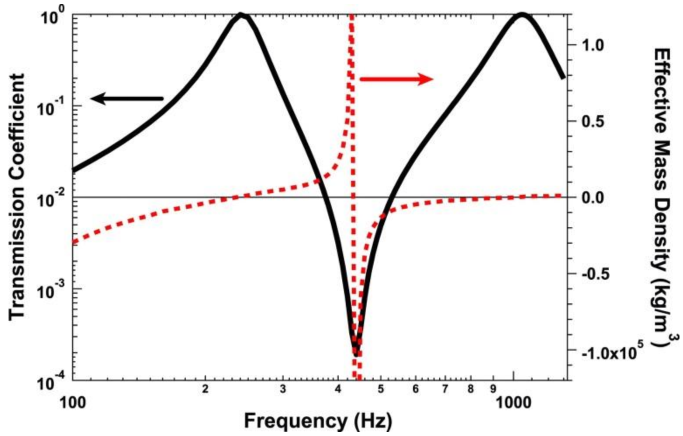


**Figure 3** The effective dynamic mass of the membrane-type acoustic metamaterial (red symbols, right axis), together with the transmission coefficient (black solid curve, left axis), evaluated with an incident wave with pressure modulation amplitude of 1 Pa. Adapted from Ref. 32.

How about absorption of low frequency sound by membrane-type acoustic metamaterials? Linear response dictates that the absorption coefficients must be small at low frequencies. Hence to absorb effectively we must have high energy density. This is usually achieved by using resonances. However, resonance in enclosed cavities can have difficulties in coupling to the incident wave, whereas the usual resonances in open geometry, such as the membrane resonances in our acoustic metamaterials, would couple strongly to radiating modes. In either case the absorption is weak. By utilizing highly concentrated *curvature energy* that can occur at the perimeters of the decorated metallic platelets as seen in Fig. 4, we have achieved very high absorption of low frequency sound[35]. This is because (1) the curvature energy is proportional to the second spatial derivative of $w$, squared, which implies energy density that can be orders of magnitude higher than the incident wave energy density; and (2) the regions in which the energy is concentrated can only couple to the evanescent waves, as can be deduced from the arguments presented above. Hence in this particular case we essentially have open cavities that can concentrate energy and couple to the incident wave effectively, and yet do not radiate.

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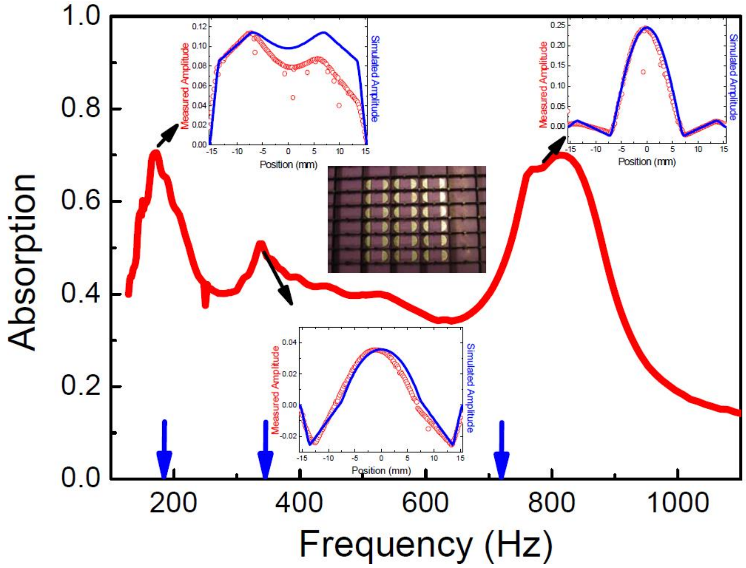


**Figure 4** Red curve denotes the measured absorption coefficient. There are 3 absorption peaks located at 172, 340, and 813 Hz. Blue arrows indicate the positions of the absorption peak frequencies predicted by finite-element simulations. The cross-sectional profiles of w along the x axis of the unit cell are shown in the insets for each of the three resonances. The straight sections (7.5mm ≤|*x*|≤ 13.5 mm) of the profile indicate the positions of the platelets. Red circles denote the measured profile by laser vibrometer, while blue curves are the finite-element simulation results. Kinks in the profiles are clearly seen, indicating regions of high curvature energy. A photo image of the sample is shown in the inset at the center of the figure. Adapted from Ref. 35.

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