

# A Review on Acoustic Metamaterials

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## ABSTRACT

In the recent past, static properties of the materials primarily driven the material selection. However, what these static properties failed to satisfy found realized by their complementary parts, dynamic properties. Direct consequence of such realization vis-à-vis electromagnetic waves give evolution to Metamaterials. Metamaterials are on buzz for its fascinating extra physical application and possibilities. The core concept of Metamaterial is to replace the molecules, the basic building blocks, in conventional materials, with man-tailored structures usually viewed as ‘artificial atoms’ on a scale much smaller than the relevant wavelength. This way, less number of effective parameters describes Metamaterial.

Developed almost in parallel to the electromagnetic counterparts, Acoustic Metamaterials (AMMs) primarily deals with the mechanical waves to cater the needs of Sound Control and Management. The beginners in the field quickly found that certain concepts could not be anticipated from electromagnetics, such as penta-mode materials (exotic materials that only resist one mode of deformation, analogous to how fluids only resist volumetric change), to address AMM challenges.

The methodology followed in this review is:

1. Categorisation of the entire literature review on AMMs in accordance to the following unconventional design spaces recognised by 2D-graph for density ( $\rho$ ) versus compressibility (C):
  - a) Single Negative Materials (Space quadrant 2 and 4 of such a graph)
  - b) Double Negative Materials (Space quadrant 3, of the said graph)
  - c) Zero Indexed Materials (Origin of the graph)
2. Eloquent presentation of the collected data, using tables and figures for compact, comprehensive and comparative evaluations.

**Keywords:** Acoustic Metamaterials; Sound Management and Control; Single Negative, Double Negative, Zero Indexed Materials.

## 1. INTRODUCTION

The launch of Metamaterials is marked by the famous paper by Sir John Pendry<sup>1</sup>, published in the year 2000. It came after over 30 year’s ignorance of Vassalage’s visionary proposal on a similar topic. However, within 10 years of Pendry’s paper, Metamaterials developed in to a

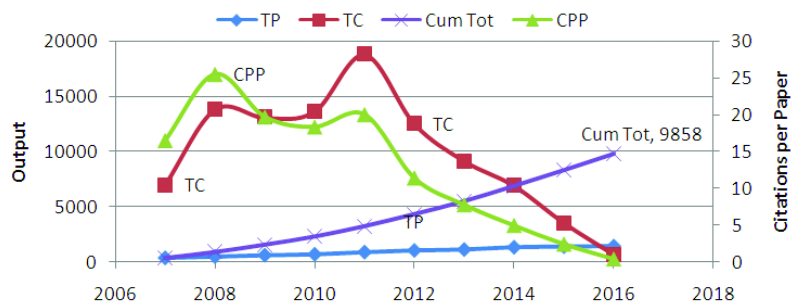
breakthrough technology for their potentials for cloaking and light manipulation<sup>2-6</sup>. With the new technology taking shape, more and more applications have emerged in telecommunication, sensing, aerospace, optics (terahertz and infrared), and medical instrumentation. Metamaterials also show great potential for application in the military and defence in addition to their industrial counterparts<sup>7</sup>.

## 2. LITERATURE REVIEW

AMMs research was originally motivated by parallel developments in electromagnetics, such as negative refraction and cloaking<sup>8</sup>. The beginners in the field quickly found that certain concepts could not be anticipated from electromagnetics, such as penta-mode materials (exotic materials that only resist one mode of deformation, analogous to how fluids only resist volumetric change), to address AMM challenges<sup>8,9</sup>.

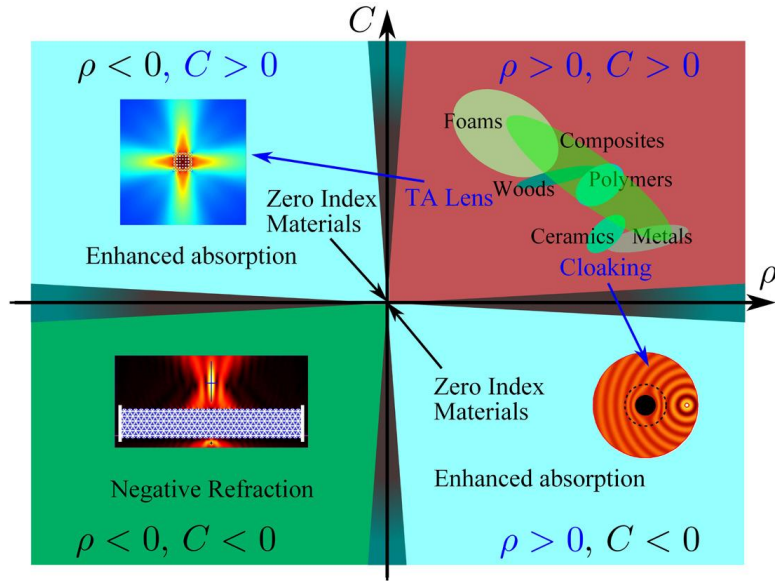
The wave nature of both sound and light are fundamentally related. Accordingly, it wasn't long after the first investigations on electromagnetic metamaterials were published until the first acoustic metamaterials were developed by Liu et al.<sup>10</sup>.

According to a recent study, metamaterials is still a nascent and emerging research field, which is multi-disciplinary in nature. It involves disciplines such as physics (59.36%), engineering (56.71%), materials science (33.30%), computer science (20.32%), mathematics (6.74%) and chemistry (4.46%). According to this survey, global literature in 10 years did not grow as high as expected but it could cumulate its global output to 9858 publications with 15.27% growth during 2007-16. Most disappointing trend revealed by the graph in the figure 1 is, that despite growth in the publication, total citation or citation per paper are on decline. This clearly exhibit the declining interest of the researchers or the quality of the output<sup>11</sup>.



**Figure 1.** Publications and citations growth in metamaterials: 2007-16 (TP = Total papers; TC = Total citations; CPP = Citations per paper; Cum Tot = Cumulative Total)<sup>11</sup>.

The following figure shows the design space for the Acoustic Metamaterials with examples:



**Figure 2:** The material design space for acoustic metamaterials: Density,  $\rho$  Versus Compressibility,  $C$  (inverse of the Bulk modulus,  $B$ )<sup>9</sup>.

Only possibility to achieve Negative density or compressibility is dynamically. For instance, Helmholtz resonators driven just above their frequency of resonance lead to negative dynamic compressibility. The three devices shown, employ the metamaterial effects of negative refraction, transformation acoustics (TA), and cloaking<sup>9</sup>.

The two essential parameters of acoustic materials (the analogues to the permittivity and permeability of electromagnetic materials are the mass density,  $\rho_0$  and the bulk modulus,  $B_0$ ). These two determines all the relevant acoustic material parameters such as<sup>12</sup>:

$$\text{The phase velocity (or speed of sound), } c_0 = \sqrt{(B_0/\rho_0)} \quad -(1)$$

$$\text{The wave number, } k_0 = \omega/c_0 = \omega\sqrt{(\rho_0 / B_0)} \quad -(2)$$

$$\text{And the characteristic impedance, } Z_0 = \rho_0 c_0 = \rho_0 \omega/k_0 \quad -(3)$$

Appreciated from these relationships, negative values for  $\rho_0$  and  $B_0$  have some remarkable consequences on the acoustical properties of the material. For example, single-negative acoustic metamaterials, i.e. acoustic metamaterials with either  $\rho_0$  or  $B_0$  being less than zero, exhibit an imaginary wave number and, consequently, acoustic waves cannot propagate inside an unbounded domain of such a material<sup>12</sup>.

Entire Literature review can be categories in accordance to the design space shown in the figure 2 above<sup>10</sup>. Accordingly, unconventional categories are:

1. Single Negative Materials.
2. Double Negative Materials.
3. Zero Indexed Materials.

## 2.1 SINGLE NEGATIVE MATERIALS

For the development of the basic understanding, in accordance to the outcomes of Xiuhai Zhang et al. and Mei et al. 2012, the absorption type AMMs can be categorised into the following sub-categories<sup>13,14</sup>:

- 1) Airborne sound absorbing AMMs.
  - (a) Membrane-type AMMs (with no mass attached on the elastic membrane, Type -1) and (with mass attached on the elastic membrane, Type -2)
  - (b) Sonic crystals.
- 2) Waterborne sound absorbing AMMs.
- 3) Gradient-index sound absorbing AMMs.

### 2.1.1 AIRBORNE SOUND ABSORBING AMMs

#### 2.1.1.1 Membrane-Type AMMs

Membrane-type AMMs are usually mass embedded elastic membranes, forming analogous spring-mass systems. Membrane-type AMMs are considered, initially, reflective metamaterials for sound insulation<sup>15,16</sup>. To extend the absorption function of membrane-type AMMs, Sheng's group proposed an absorber consisting of an elastic membrane decorated with asymmetric rigid platelets<sup>14</sup>. Findings under this category can be summarised as follows:

**Table 2.1.1.1:** Membrane Type AMMs.

Criterion	Membrane-type AMMs, Type -1	Membrane-type AMMs, Type-2
Governing Equation*	$\rho_{\text{effective}} = \rho(1 - \omega_0^2/\omega^2)$	$\rho_{\text{effective}} = \frac{1}{Ad} [M + m(\omega_0^2/\omega^2 - \omega^2)]$
Key findings	For, $0 < \omega < \omega_0$ ; $\rho_{\text{effective}} < 0$ <ul style="list-style-type: none"> <li>• Obtained negative density in a broadband frequency; hence, the mass frequency law is broken for the said range.</li> <li>• No transmission due to imaginary wave number.</li> </ul> For, $\omega = \omega_0$ ; $\rho_{\text{effective}} = 0$ <ul style="list-style-type: none"> <li>• Wave number tends to infinite; and impedance of the system tend to be zero; hence maximum transmission. Attenuation at resonance frequency.</li> </ul>	For, $\omega_0 < \omega < \omega_0 \sqrt{[(M+m)/M]}$ ; $\rho_{\text{effective}} < 0$ <ul style="list-style-type: none"> <li>• No transmission due to imaginary wave number.</li> </ul> For, $\omega = \omega_0 \sqrt{[(M+m)/M]}$ ; $\rho_{\text{effective}} = 0$ <ul style="list-style-type: none"> <li>• Resonance attained at non-resonant frequency.</li> <li>• Maximum Transmission as the apparent impedance is zero.</li> </ul>
		<ul style="list-style-type: none"> <li>• Response of the cell depends upon the applied tension, a dynamic property, with a possibility to tune on real time basis.</li> </ul>
Variants	<ul style="list-style-type: none"> <li>• <b>Metasurface</b><sup>17</sup>: This membrane type metasurface can obtain perfect absorption at specific frequencies under 500 Hz, and the absorbed acoustic energy can be converted to electrical current. In their work, they observed high acoustic-electrical energy conversion efficiency as 23%.</li> <li>• <b>Cavity backed</b><sup>18</sup>: For a membrane type AMM with a large back cavity, magnetic negative stiffness could be employed to reduce the back cavity size and shift the absorption peak to lower frequencies.</li> <li>• <b>Employing Adaptive stiffness</b><sup>19</sup>: Adaptive stiffness of AMMs could be employed to broaden low-frequency sound absorption.</li> <li>• <b>Employing Acoustic siphon effect</b><sup>20</sup>: The acoustic siphon effect could be employed to reduce the thickness of units of a membrane-type AMM.</li> </ul>	

Potential Applications	<p>a) Filters in sensor and transducers:</p> <ul style="list-style-type: none"> <li>• High pass filter can be made from membrane AMM, type-1, for sound synthesiser and audio mixers.</li> <li>• Possibility to build band-pass filters from the membrane AMM, type -2, for use in wireless transmission and reception.</li> </ul> <p>b) Low frequency noise reduction: Machine (s) noise reduction etc.</p> <p>c) Sound proofing: Wall coatings etc.</p> <p>d) Acoustic reflectors (Acoustic mirrors): To develop sweet spots etc. to enhance audibility.</p>
<p><math>\rho_{\text{effective}}</math>: Effective density of the unit cell; <math>\rho</math>: Net density of the unit cell; <math>\omega_0</math>: Natural angular frequency of the unit cell. <math>\omega</math>: Instantaneous angular frequency of the cell; A: surface area of the membrane; d: Length of the unit cell; M: Mass of the enclosed air and membrane; m: Mass attached to the membrane.</p>	

### 2.1.1.2 Sonic Crystals

**Table 2.1.1.2:** Sonic Crystals.

Criterion	Sonic Crystal
Working Principle	<p>Effective negative bulk modulus, <math>B_0</math> achieved in accordance to the <b>Bloch Theorem</b> and inciting <b>local resonance</b> in the crystal.</p> <p><b>Bloch Theorem:</b> The acoustic field inside a symmetrical periodic structure take the same symmetry and periodicity as the structure itself. Hence, a strong periodic modulation in density and /or bulk modulus can create spectral gaps (frequency bands) that forbids wave propagation for the corresponding frequencies.</p> <p><b>Bloch Waves:</b> Bloch waves are corresponding periodic waves.</p> <p><b>Bloch Wave's Characteristics:</b></p> <ul style="list-style-type: none"> <li>• Such quantised waves exists in discrete modes called Bloch modes.</li> <li>• Bloch modes must have same periodicity as the periodic crystal i.e. <math>\lambda</math> will be same for all such waves. Which implies that wave number, <math>k = 2\pi / \lambda</math> will also be same.</li> <li>• Acoustic intensity of the lowest order mode tends to reside in acoustically denser region i.e. regions with higher acoustic impedance. Also Acoustic intensity, <math>I = P_{\text{(avg.)}}^2 / \rho c</math>, where average pressure, <math>P_{\text{(avg.)}}</math> (same waveform) and <math>\rho</math> (occurs in same periodic structure) are same for the different wave modes. Hence, for different intensity for the different modes, <math>c</math> has to different. Therefore, angular frequency, <math>\omega = kc</math>, of the waves in different modes will be different.</li> <li>• Thus, allowable frequencies are discrete and separate.</li> <li>• No wave propagation occurs through the crystal over such frequency bands, that known as band gaps.</li> <li>• <b>Limitations</b> Such theorem is applicable only when spacial modulation is the order of the target wavelength in the band gap. The typical environment noise sources e.g. machine sources are between frequencies 100 – 2000 Hz (equivalent to <math>\lambda</math> of 3.4 cm to 17 cm). Hence, sonic crystal has to be size of outdoor sculptures (physical and economic constraints).</li> <li>• <b>Alternative</b> (to above limitation), incitation of <b>local resonance</b> i.e. locally resonating the unit cells such that negative effective bulk modulus and or negative effective density is achieved.</li> <li>• Such sonic crystals exhibit spectral gaps with lattice constraints 2 order of magnitude smaller than the target frequency.</li> </ul>
Controlling Factors	<ul style="list-style-type: none"> <li>• Filling Fraction</li> </ul> <p>i) Size of the scatterer.</p> <p>ii) Lattice constant.</p> <ul style="list-style-type: none"> <li>• Geometry of the sonic scatterer.</li> <li>• Type of the lattice system.</li> <li>• Presence of the defects in the crystal lattice.</li> </ul>

Experimental Observations [50,51] <sup>21,22</sup>	<ul style="list-style-type: none"> <li>• Keeping other factors constant, a larger filling fraction leads to wider band gap.</li> <li>• <b>Defect band</b>, frequency band corresponding to the defect in the crystal, tone (constant resonance frequency) exists within the absolute band gap.</li> <li>• There is a possibility to control locations of such tones within the defect band through varying the unit cell size.</li> <li>• Varying the lattice type results in the appearance of another band gap.</li> </ul>
Variants	<ul style="list-style-type: none"> <li>• <b>Solid scatterers</b><sup>23,24</sup>: AMMs can be grouped into solid-solid, fluid-fluid, and solid-fluid composite systems. For solid-fluid AMMs, when characteristic structures (usually regular structures) of AMMs are solid, AMMs considered to have consisted of solid scatterers embedded in a fluid matrix. Early research into AMMs based on solid scatterers focused on the band gap, which have possibility for sound attenuation in a specific frequency range. Local resonance for sound attenuation in AMMs was a research hotspot.</li> <li>• <b>Employment of thermo-viscous effects</b><sup>25</sup>: The inherent losses arising from thermal and viscous effects in AMMs were also applied to absorb acoustic energy.</li> <li>• <b>Combination with other sound absorbing materials</b><sup>26</sup>: Embedding steel spheres into porous foam could improve low-frequency sound absorption.</li> <li>• <b>Varying shapes of solid inclusions</b><sup>27</sup>: The effects of shapes of solid inclusions on sound absorption were further studied.</li> <li>• <b>Added perforated shells</b><sup>28</sup>: Exhibit high absorption levels.</li> <li>• <b>Varying crystal filling fraction, scatterer's coating layer, and type of backing</b><sup>10,29</sup>: These are additional specific studies into the factors influencing AMMs sound absorption performance.</li> </ul>
Potential Applications	<ul style="list-style-type: none"> <li>• Sound attenuation.</li> <li>• Noise barrier.</li> <li>• Sound bending.</li> <li>• Acoustic wave guides.</li> <li>• Acoustic Imaging.</li> </ul>

### 2.1.2 WATERBORNE SOUND ABSORBING AMMs

Waterborne sound absorbing materials are in great demand in underwater acoustic communication system, sonar evasion, and other applications. However, research on waterborne sound absorbing materials progresses slowly due to the complex marine environment and high hydrostatic pressure. Benefiting from developments in AMMs, waterborne sound absorbing materials has shown new developments<sup>13</sup>.

**Table 2.1.2:** Waterborne Sound Absorbing AMMs

Variants	<ul style="list-style-type: none"> <li>• <b>Air bubbles for sound absorption</b><sup>30</sup>: Demonstrated an AMM with air bubbles for sound absorption, and the high absorption (higher than 91%) was obtained over the 1.4–2.9 MHz range.</li> <li>• <b>Air-filled cavities covered by rubber coating</b><sup>31</sup>: Could be used as anechoic submarine coatings.</li> <li>• <b>Spheres coated by viscoelastic matrix</b><sup>32</sup>: High-density spheres coated by viscoelastic matrix are an effective method for waterborne sound absorption.</li> <li>• <b>Under water acoustic metasurface</b><sup>33</sup>: Recently, an acoustic metasurface, consisting of a metal grating covered with a polydimethylsiloxane layer, was proposed and exhibited high absorption over 0.5–10 MHz</li> <li>• <b>LRPW</b><sup>34</sup>: Locally Resonant Phononic woodpile was proposed to enhance the underwater sound absorption in a wide frequency range. The LRPW consisted of steel rods with three different sizes, soft polyurethane (PU), and hard PU. The LRPW proved to possess strong underwater acoustic absorbance with the absorption coefficient over 0.8 from 8 to 30 kHz.</li> <li>• <b>Composite structure interpenetrating network</b><sup>35</sup>: Proposed a composite structure that combined the locally resonant PC and interpenetrating network structure to achieve a broadband underwater strong acoustic absorption.</li> </ul>
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### 2.1.3 GRADIENT-INDEX SOUND ABSORBING AMMs

Although AMMs impart extraordinary properties, most of those properties are usually single frequency or narrow band because high absorption would occur only near resonant frequencies. Proposed gradient-index structures for AMMs overcome such limitation. Modulating the characteristic factors, such as the radii or elastic properties of the inclusions, the lattice spacing or width, orientation angle, and thickness shows possibility to achieve Gradient-Index AMMs. For an absorbing material based on the dissipative effect, there are two important conditions for excellent sound absorption: Superior dissipation capacity within the material and little reflection at the fluid-structure interface. Therefore, no matter how good dissipation capacity of the material is, the sound absorption can be weak if significant reflection occurs at the fluid-structure interface. Hence, impedance matching at fluid-structure interface is crucial in sound absorption<sup>13</sup>.

For analysis of the Gradient Index AMMs, Xiuhai Zhang et al. presented the data on such materials in the tabulated form as shown below<sup>13</sup>:

**Table 2.1.3:** Gradient-Index Sound Absorbing AMMs.

Method for Achieving Gradient-Index Structures	Material of Inclusions	Material of Matrix	Max. Shape Size along with Incident Wave (mm)	Function
Modulating radii of the inclusions <sup>36</sup>	Plastic	Air	240	Focusing the acoustic wave into the dissipated core
Fin-like structure <sup>37</sup>	Acrylonitrile butadiene styrene	Air	514.6	Focusing the acoustic wave into the dissipated core
Modulating radii of the inclusions <sup>38</sup>	Rubber	Water	356	Focusing the acoustic wave into the dissipated core
Modulating radii of the inclusions <sup>39</sup>	Aluminium rod	Air	1,480	Improving sound absorption
Modulating radii of the inclusions <sup>40,41</sup>	Air	Photosensitive resin	30	Broadening and improving sound absorption
Modulating cross-section <sup>42</sup>	Poly lactide	Air	40	Broadening sound absorption
Modulating thicknesses of the porous layer <sup>43,44</sup>	Porous material	Air	70	Broadening and improving sound absorption
Modulating height of the saw-tooth <sup>45</sup>	Thermoplastics	Air	370	Broadening sound absorption

## 2.2 DOUBLE NEGATIVE MATERIALS

Double-negative AMMs offer the promising ability of super-lensing for applications in ultrasonography, biomedical sensing and non-destructive evaluation. However, the

systematic design and realization of broadband double-negative AMMs is still missing, which hinders their practical implementations.

**Table 2.2:** Double Negative Materials.

<b>DOUBLE NEGATIVE MATERIALS</b>	
Topology optimization framework <sup>46</sup>	<ul style="list-style-type: none"> <li>• By simultaneous increasing or non-increasing mechanisms, develop a unified topology optimization framework considering the different microstructural symmetries, minimal structural feature sizes and dispersion extents of effective parameters. They experimentally shown the desired broadband subwavelength imaging using the 3D-printed optimized space-coiling metamaterial. The presented design methodology provides an ideal approach for constructing the constituent ‘atoms’ of metamaterials according to any manual physical and structural requirements. In addition, the optimized broadband AMMs and super-lens can truly lay the structural foundations of subwavelength imaging technology.</li> <li>• They also demonstrated the essences of double negativity derived from the novel artificial multipolar LC (inductor-capacitor circuit) and Mie resonances. Which shows possibility to induce by controlling mechanisms in optimization.</li> <li>• Furthermore, abundant numerical simulations validate the double negativity, negative refraction, enhancements of evanescent waves and subwavelength imaging for the optimized AMMs.</li> </ul>
Acoustic duct <sup>9</sup>	<ul style="list-style-type: none"> <li>• Proposed an acoustic duct with alternating membrane masses and Helmholtz resonators. The resonances of the two elements produce negative effective density and effective compressibility in certain frequency ranges. Simultaneously negative density and compressibility, a ‘double-negative material’, shows possibility to obtain by matching the resonances.</li> </ul>

### 2.3 ZERO INDEXED MATERIALS

Zero index materials are of interest because the phase speed becomes infinite (index is zero). This allows for devices that can steer acoustic energy in unusual ways, such as unidirectional transmission and cloaking<sup>47</sup>.

**Table 2.3:** Zero Indexed Materials.

<b>ZERO INDEXED MATERIALS</b>	
Acoustic duct <sup>9</sup>	<ul style="list-style-type: none"> <li>• The alternating Membrane masses and Helmholtz resonators proposed by authors realising double negative AMMs also allow for this possibility.</li> </ul>
Doped 2D- Acoustic Crystals (solid defect) <sup>48</sup>	<ul style="list-style-type: none"> <li>• Investigated acoustic wave transmission property through a waveguide embedded with a general solid defect. Adjusting the parameters of the solid defect shows possibility to achieve total transmission and total reflection. Comprehensive study shows how longitudinal / transverse wave speeds of the solid defect affect the acoustic wave propagation through the waveguide. A two-dimensional (2D) Acoustic Crystals (ACs) system with zero index used to realize these intriguing transmission properties. The work provides more possibilities to manipulate acoustic wave propagation through ZIM.</li> </ul>
2D membrane-based Acoustic Metamaterial <sup>49</sup>	<ul style="list-style-type: none"> <li>• Numerically verified a 2D membrane-based Acoustic Metamaterial that has near zero index. Shown that the phase changes slowly in the metamaterial, indicating a large phase velocity. Also demonstrated that, around the resonance frequency, only a wave of normal direction can penetrate through the ZIM, while other incident waves found reflected. Therefore, this ZIM behaves as a perfect angular filter, which has potential to develop as an angular sensor. Such a metamaterial also shows ability to modify the radiation phase pattern according to the shape of the exit surface. In their study, they successfully manipulate a point source so that it behaves as a line source. They also pointed that better performance of their ZIM can be achieved by reducing the compressibility to a near-zero value using branch openings or open channels, such that it further increasing the effective phase velocity. According to them, this however,</li> </ul>

	necessitates a full 3D simulation that they will be address in a future study.
Coiled up space <sup>50</sup>	Reported a deferent design of ZIM by coiling up space that studies the wave tunnelling.

### 3. DISCUSSION

Most of the research work in Acoustic Metamaterials is exceedingly specialised. Accordingly need for the systematic, yet simple, representation of the same is realised. Metamaterials still are in young and growing stage. However, to excerpt its optimum potential multi-disciplinary approach is essential.

Research collaboration is essential to further the research and developments at national and international level. Besides, such a collaborative approach will help facilitate an effective use of existing resources, will additionally provide a forum for coordinated sharing, planning and joint supervision etc..

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