Sound Pressure Amplification using FP Resonance of Acoustic Metamaterial Cavity

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Physical Property Augmentation using Metamaterals

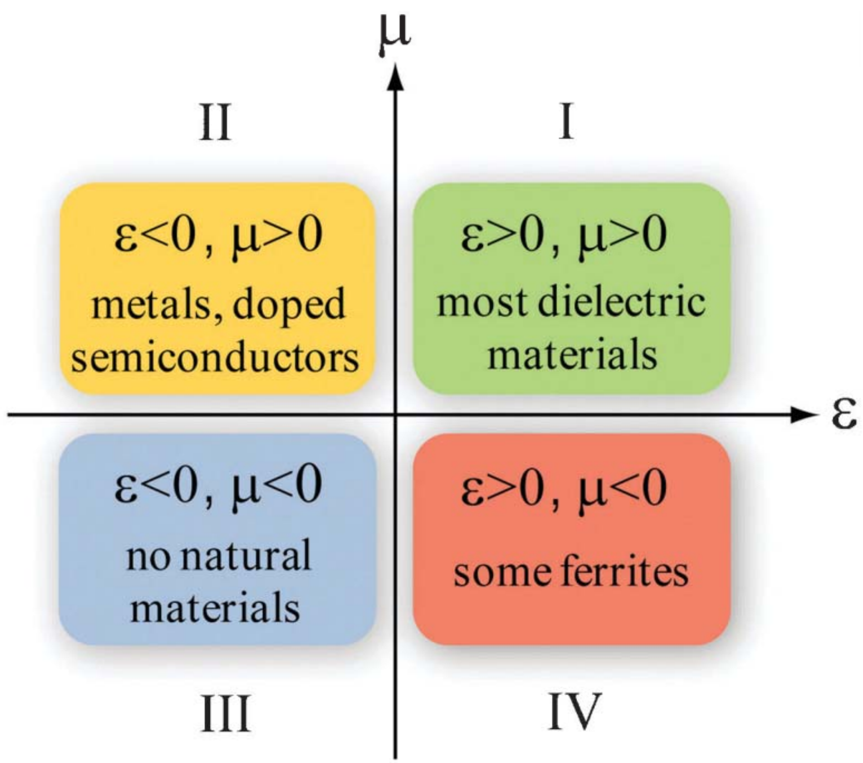
EM Property Augmentation using Metamaterials

- Metamaterials are periodic or quasi-periodic, sub-wavelength metal structures. The material properties are derived from its structure rather than inheriting them directly from its material composition.

empty glass n = 1 | regular water, n = 1.3 | "negative" water, n = -1.3

Based on definition of J.Pendry 2000

EM Property Augmentation using Metamaterials



- In electromagnetics, electric permittivity(ε), and magnetic permeability(μ) are the two fundamental parameters characterizing the EM property of a medium.
- Depending on the signs of ε and μ, materials can be categorized into 4 groups.

EM Property Augmentation using Metamaterials

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

1. INTRODUCTION

THE dielectric constant ϵ and the magnetic permea-

II. THE PROPAGATION OF WAVES IN A SUBSTANCE WITH $\epsilon < 0$ AND $\mu < 0$. "RIGHT-HANDED" AND "LEFT-HANDED" SUBSTANCES

- **The first theoretical study was performed by V.G. VESELAGO and it took nearly 30 years for experimental verification.**

EM Property Augmentation using Metamaterials

VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

Composite Medium with Simultaneously Negative Permeability and Permittivity

D. R. Smith,* Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0319
(Received 2 December 1999)

- D.R. Smith showed simultaneous negative permeability and permittivity for the first time.

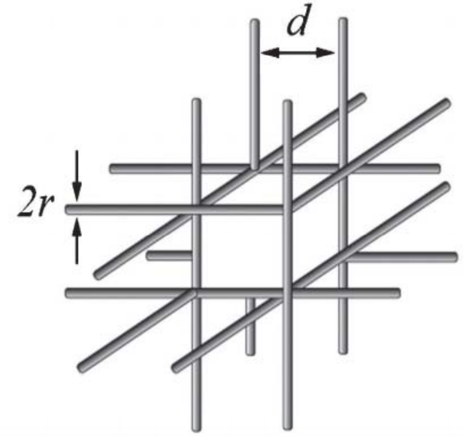
VOLUME 85, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 2000

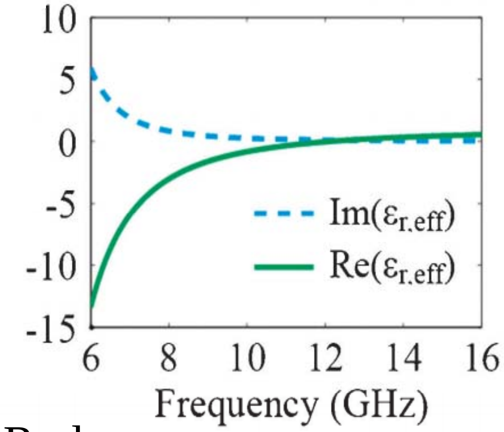
Negative Refraction Makes a Perfect Lens

J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

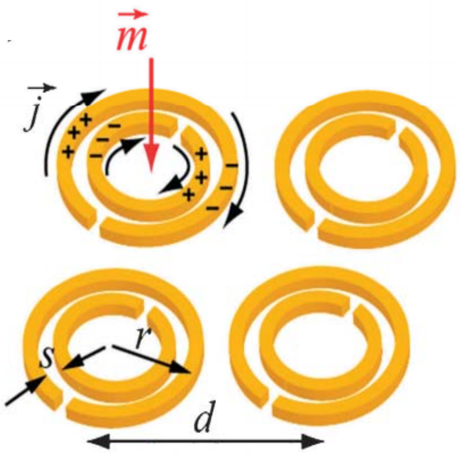
- J.B. Pendry proposed concept of perfect lens using negative refractive index and this is the most famous work in the world of metamaterials.

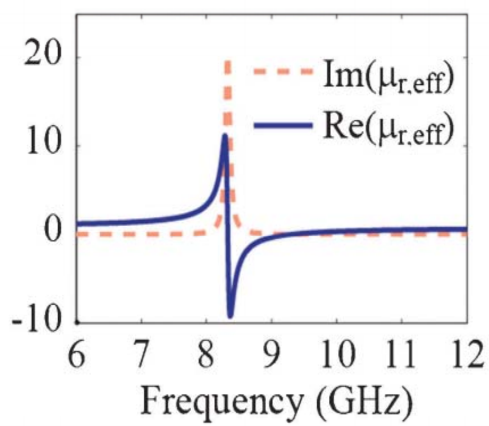
EM Property Augmentation using Metamaterials





Periodic Soilid Rods





Split Ring Resonator (SRR)

$$\varepsilon(\omega) = \varepsilon_o \left[1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \right]$$

$\omega_p = Ne^2/m\varepsilon_o$ is the plasma frequency in which the collection of electrons oscillate in the presence of electric field.

When $\gamma = 0$ and $\omega < \omega_p$ negative permittivity is achieved.

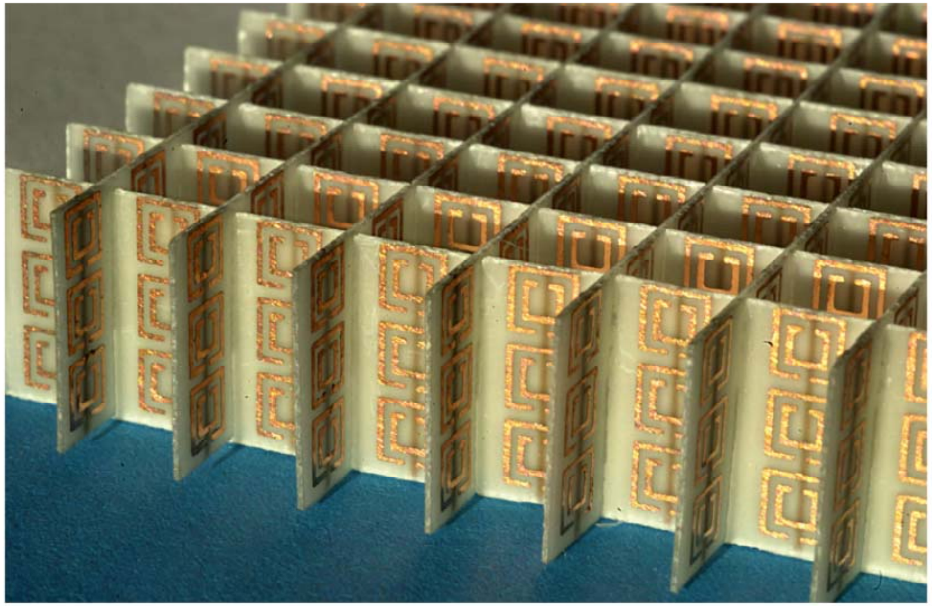
For most materials, when $\omega < \omega_p$, $\omega \ll \gamma$ (absorption dominated).

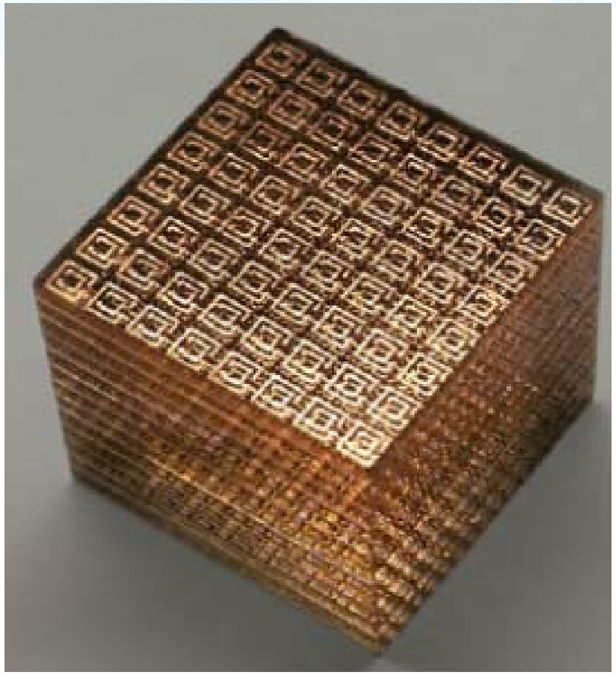
Using subwavelength periodic rods, it is possible to increase the effective mass of the electrons which decrease the ω_p .

SRRs create RLC circuit.

EM Property Augmentation using Metamaterials

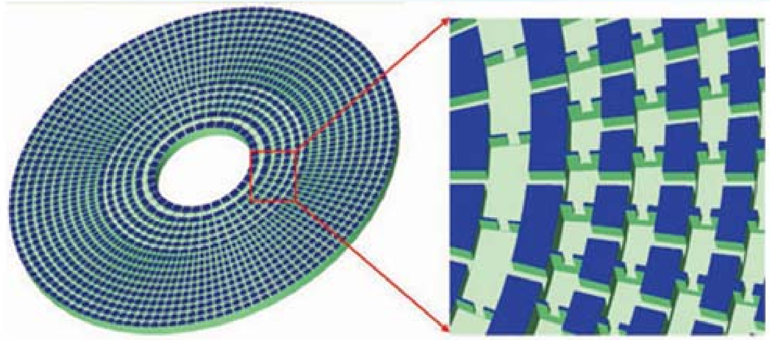
Negative refraction: $\varepsilon < 0$, $\mu < 0$

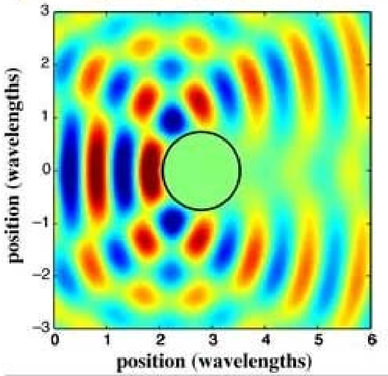


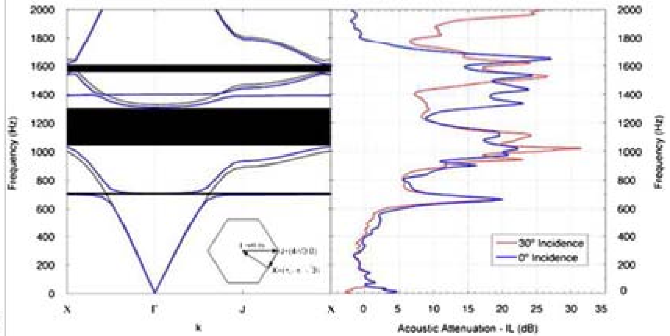


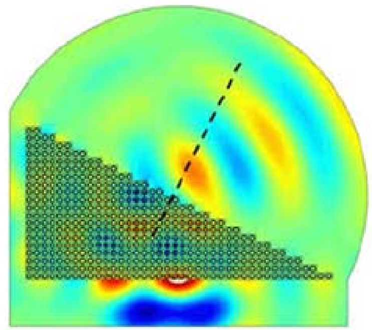
- SRR and solid rod composite material was used to achieve double negative material.
- Periodic unit cells act as ‘meta-atoms’ which show effective medium properties in subwavelength regime.

EM Property Augmentation using Metamaterials









- Many extraordinary properties are being discovered and new systems such as super lens, cloaking, reverse Doppler etc are being researched.
- However very narrow resonance bandwidth and high losses are problems for EM metamaterial systems.

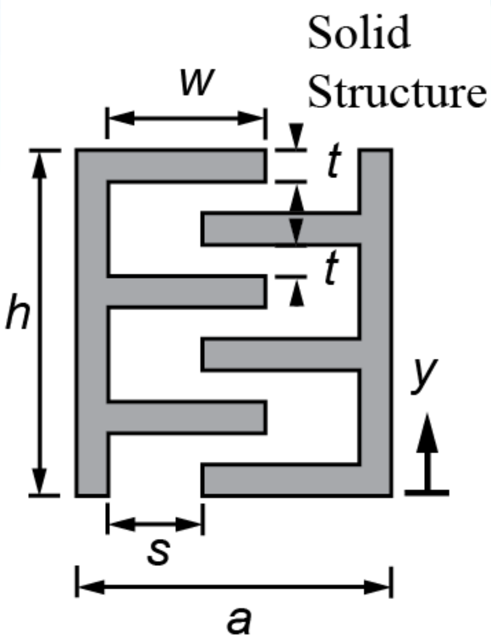
Coiled-up Space Acoustic Metamaterial Amplification Cavity

Analogy between Acoustics and EM

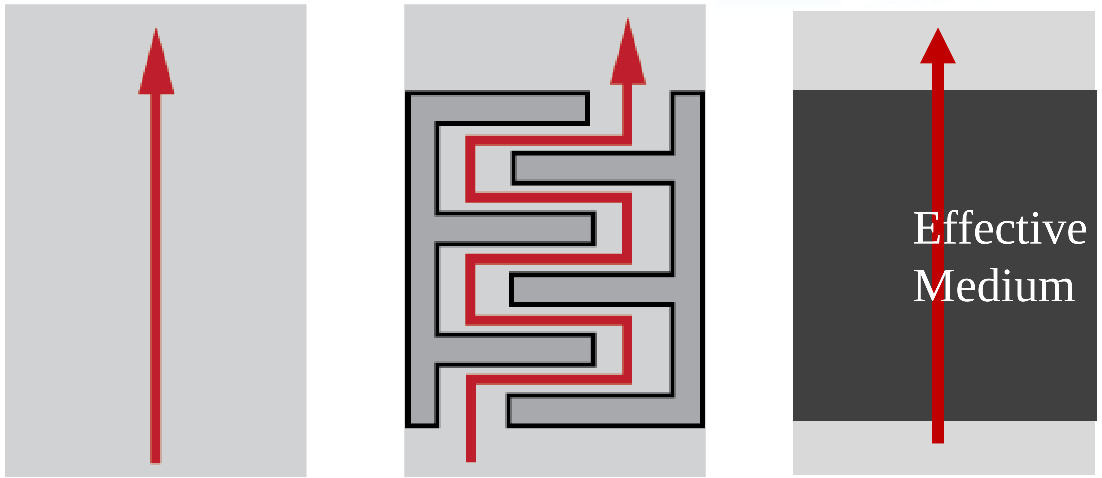
Acoustics	Electromagnetism (THz)	Analogy
$\frac{\partial P}{\partial x} = -i\omega\rho_x u_x$ $\frac{\partial P}{\partial y} = -i\omega\rho_y u_y$ $\frac{\partial u_x}{\partial x} + \frac{\partial u_x}{\partial y} = -i\omega\beta P$	$\frac{\partial E_z}{\partial x} = -i\omega\mu_y H_y$ $\frac{\partial E_z}{\partial y} = i\omega\mu_x H_x$ $\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = -i\omega\epsilon_z E_z$	
Acoustic pressure P	Electric field E_z	$-E_z \leftrightarrow P$
Particle velocity u_x, u_y	Magnetic field H_x, H_y	$H_y \leftrightarrow -u_x$, $H_x \leftrightarrow u_y$
Dynamic density ρ_x, ρ_y	Permeability μ_x, μ_y	$\rho_x \leftrightarrow \mu_y$, $\rho_y \leftrightarrow \mu_x$
Dynamic compressibility β	Permittivity ε_z	$\varepsilon_z \leftrightarrow \beta$

- **1 to 1 correspondence is possible between acoustics and Electromagnetism.**
- **Therefore many EM metamaterial related phenomenon can be replicated in the acoustic regime and more.**

Coiled-up Space Metamaterial Design



Unit Cell
(1 cm)

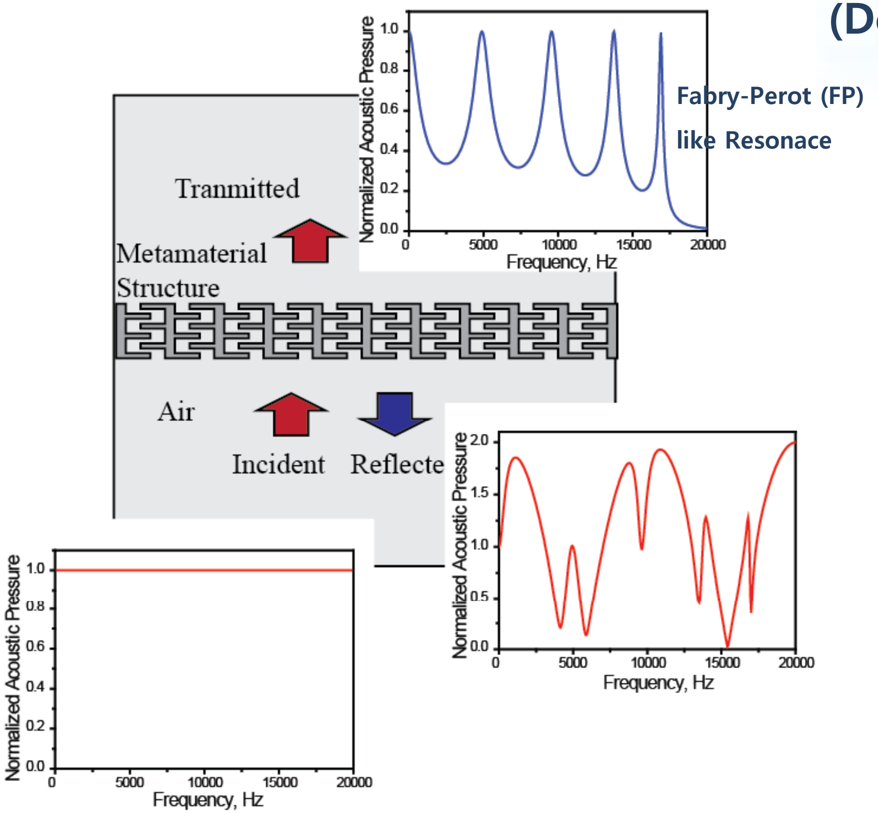


Acoustic Wave
Propagation

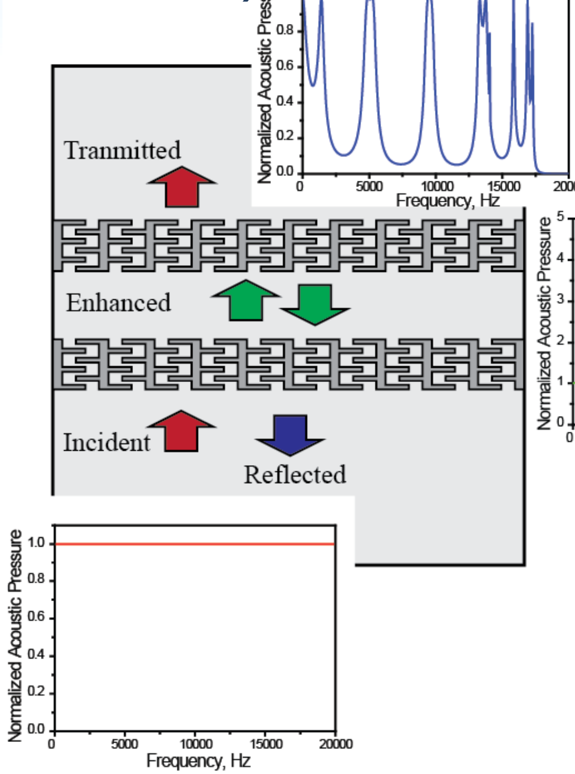
- **Solid structure which results in a 'zigzag' path is designed.**
- **Acoustic waves must travel along this zigzag path rather than the straight path.**
- **The subwavelength structure create an effective medium.**

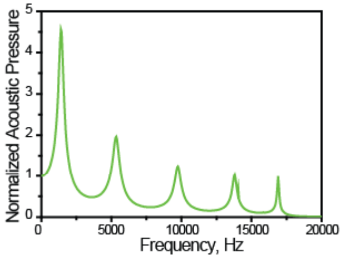
Double-fish net Metamaterial Cavity

Single-walled Metamaterial Slab



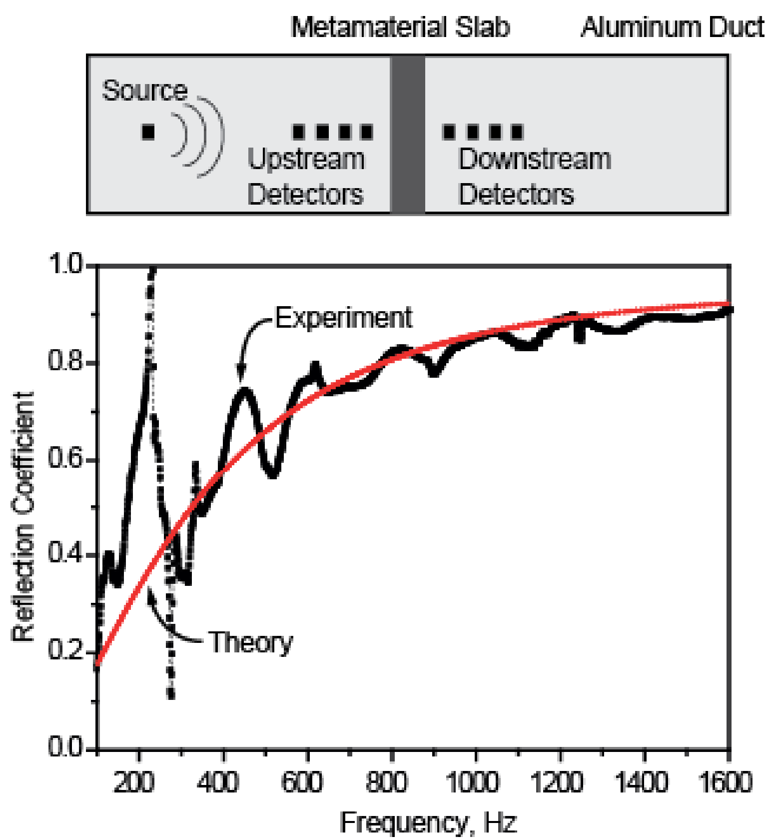
Double-walled Metamaterial Slab (Double-fish net)

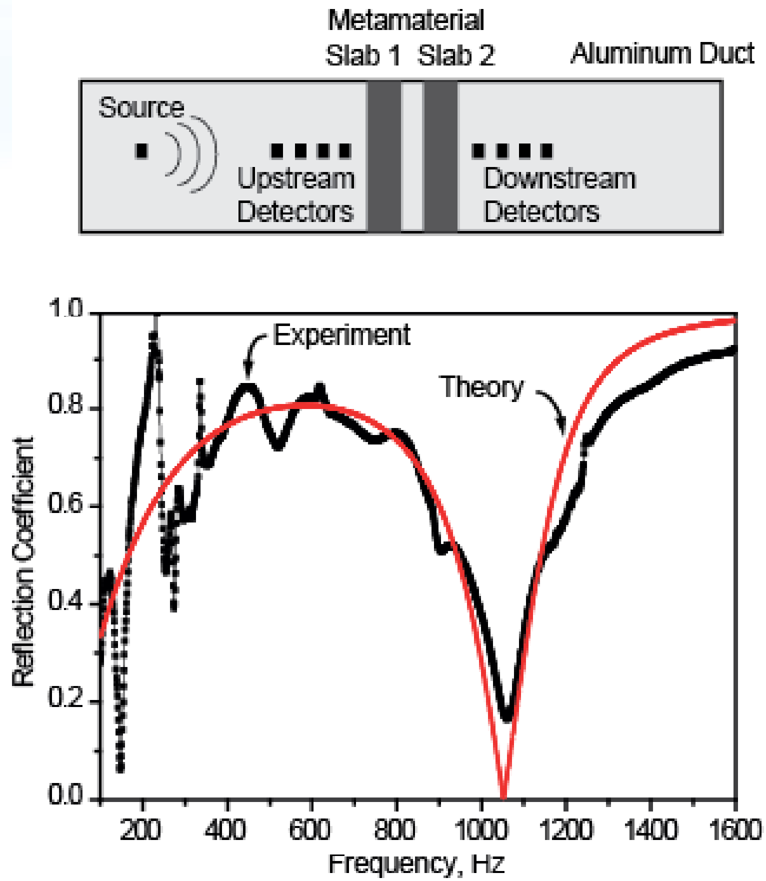




- FP like resonance modes are present for the single-walled metamaterial slab.
- FP is modified and strong amplification phenomena exists inside the cavity

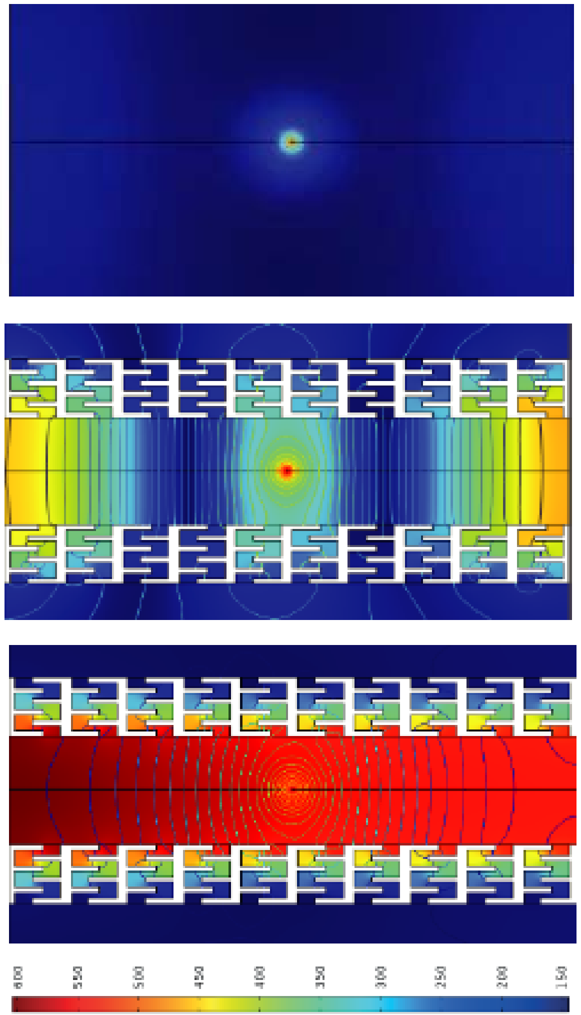
Reduced Reflection Coefficient

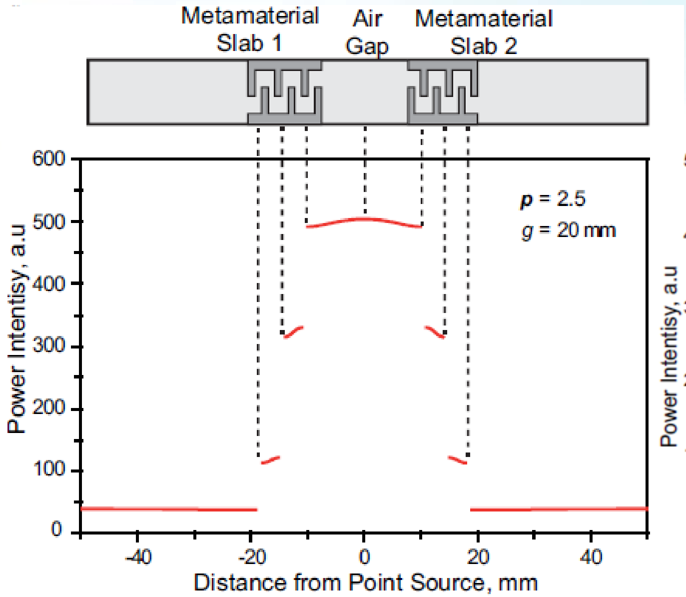


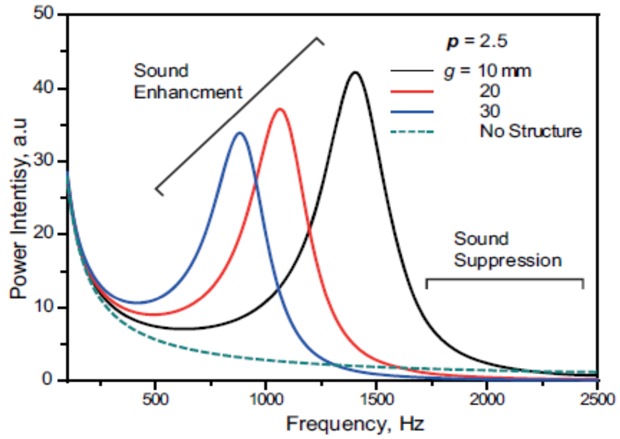


- **First experimental results show sharp drop in the reflection coefficient at the fundamental FP resonance frequency**

Emission Enhancement of Metamaterial Cavity

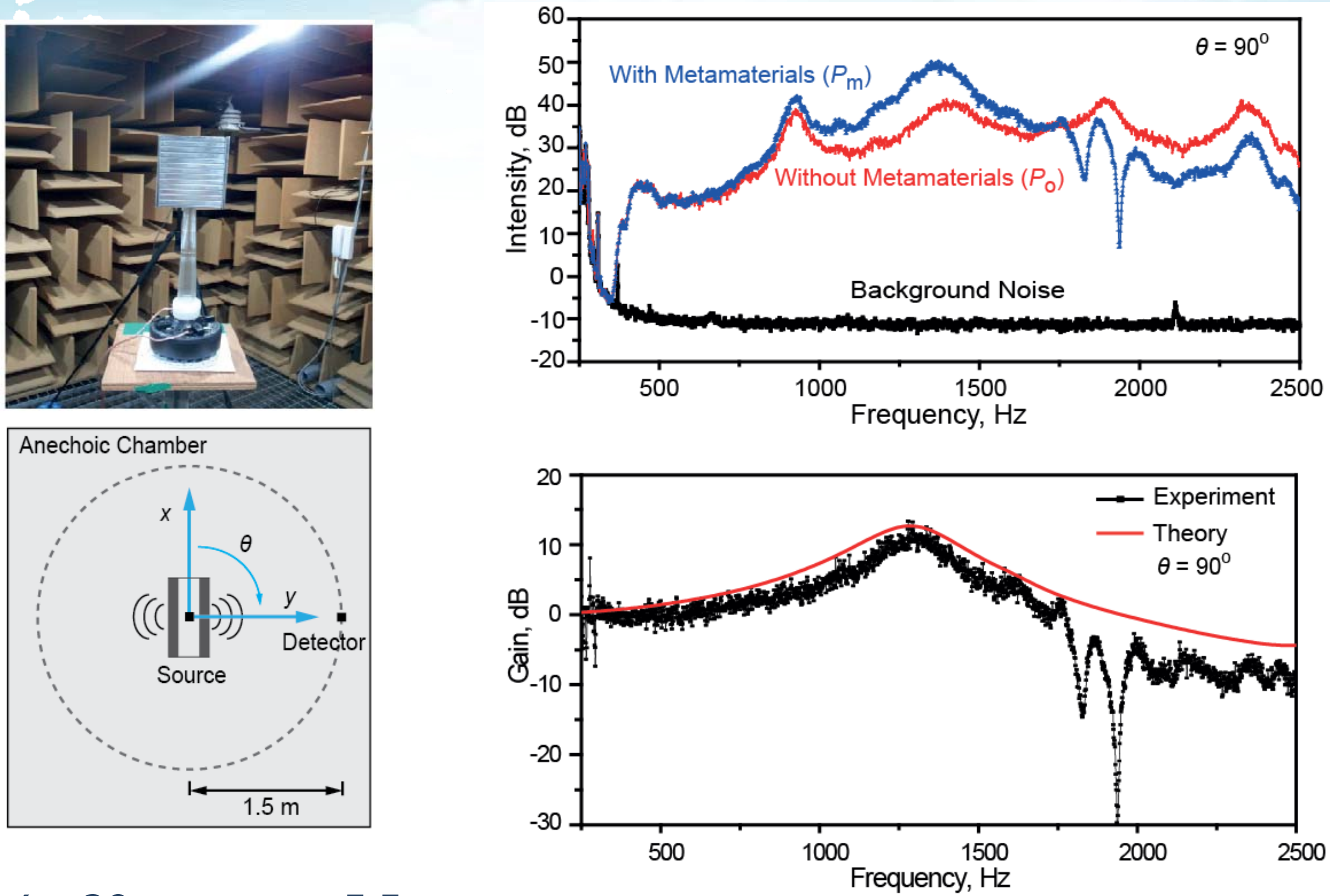






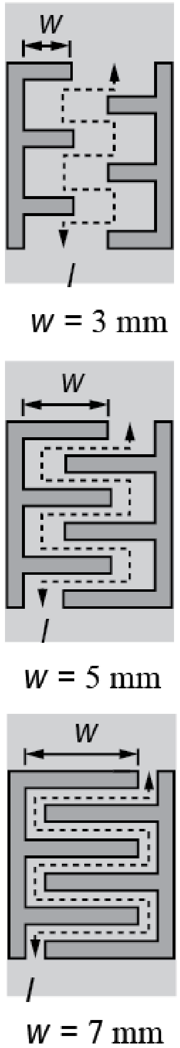
- Point source inside the cavity shows strong emission enhancement results.
- The acoustic wave field is strongly localized within the low impedance air gap.

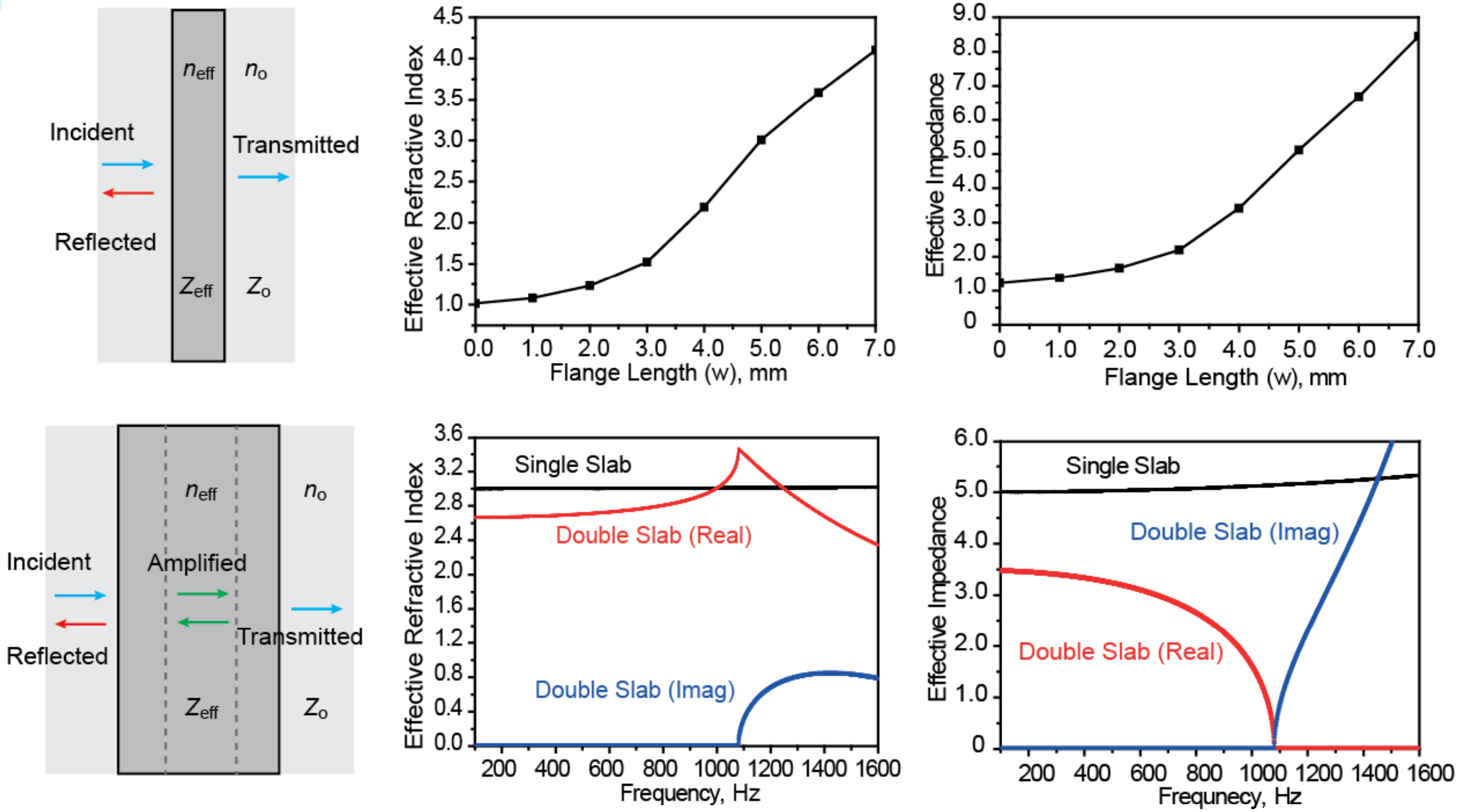
Emission Enhancement of Metamaterial Cavity



- 15 dB (x 30 power, x 5.5 pressure amplitude) emission enhancement can be achieved.
- The incident wave (1000 Hz, λ = 34 cm) can be amplified in a cavity which has unit cell size of 1 cm (1/34) and length of 4 cm (~ 1/9) subwavelength structure.

Effective Control of Refractive Index and Impedance

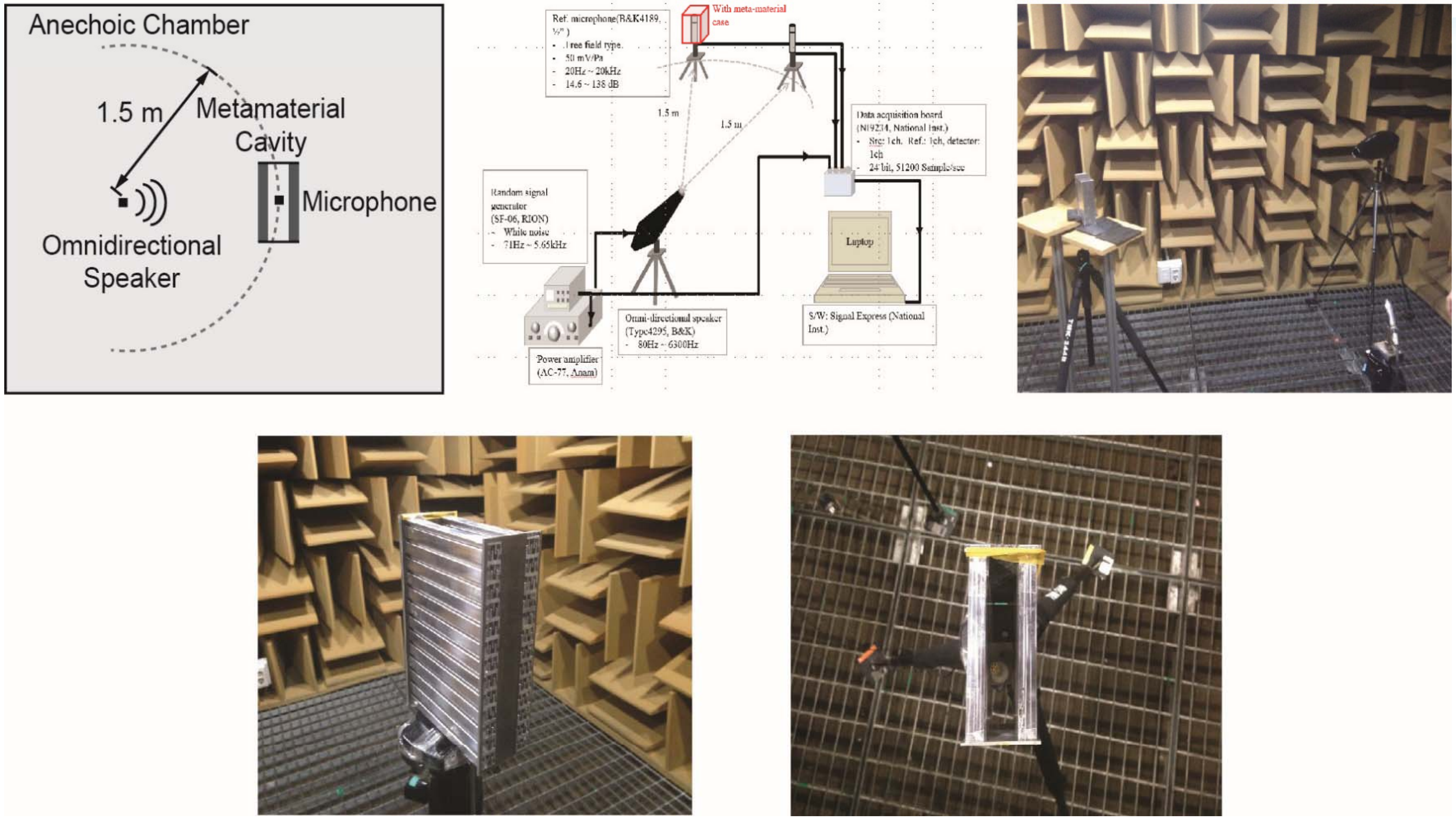




- **Increasing the path length increases the refractive index since the effective speed of sound is reduced.**

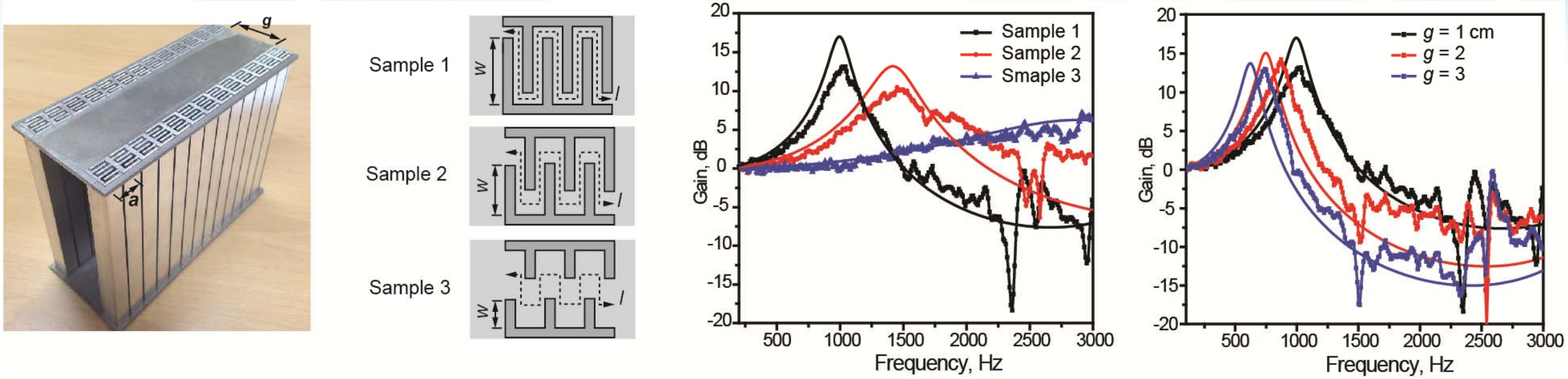
$n = c_o/c$, **where**
n = refractive index, c_o = speed of sound in reference material
c = speed of sound in medium

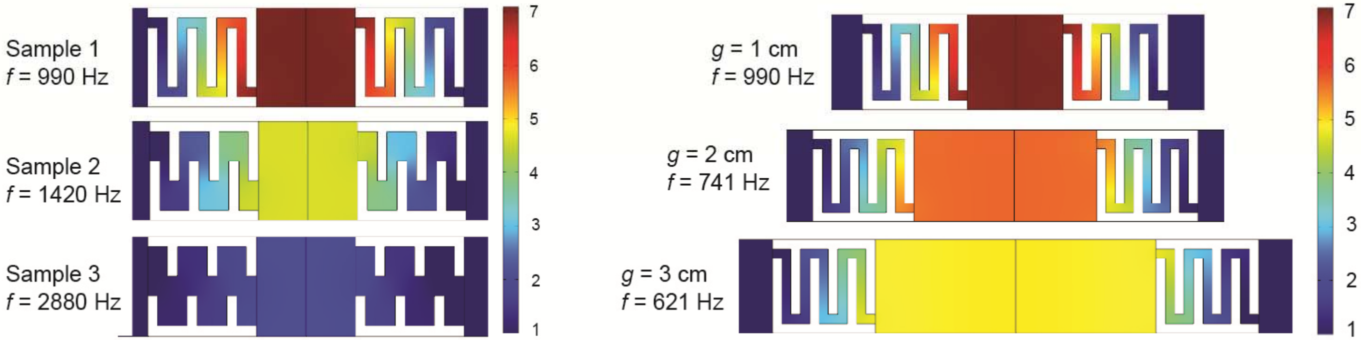
Sonic Boost using Acoustic Metamaterial Cavity



- **A microphone was place inside the metamaterial cavity to detect the amplified acoustic pressure from an outside source.**

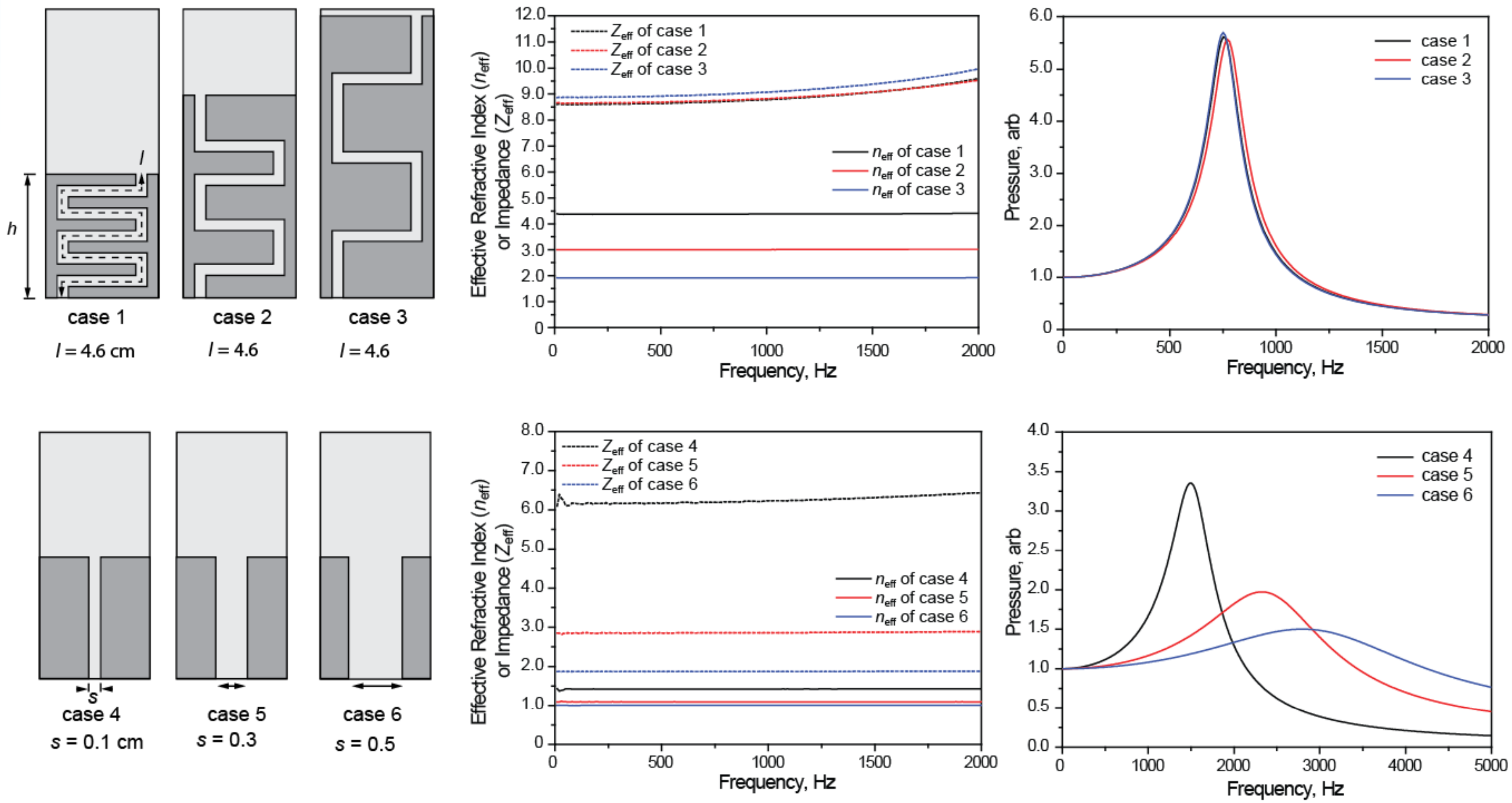
Sonic Boost using Acoustic Metamaterial Cavity





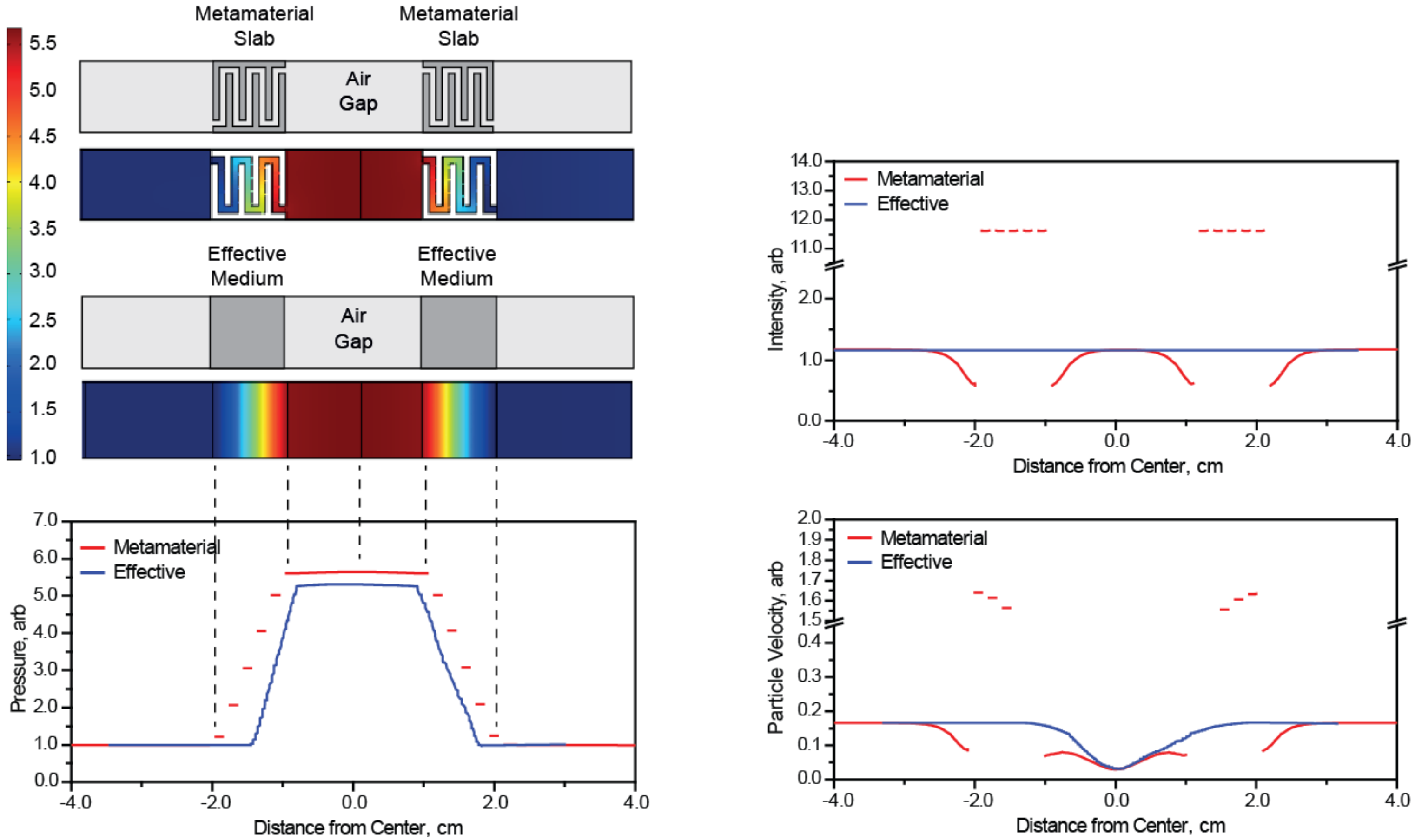
- **15 dB (x 30 power, x 5.5 pressure amplitude) emission enhancement can be achieved.**
- **The incident wave (1000 Hz, λ = 34 cm) can be amplified in a cavity which has unit cell size of 1 cm (1/34) and length of 3 cm (~ 1/10) subwavelength structure.**

Independent Control of Refractive index and Impedance



- **Strong pressure amplification due to increased impedance.**
- **High index of refraction reduces the resonance frequency.**

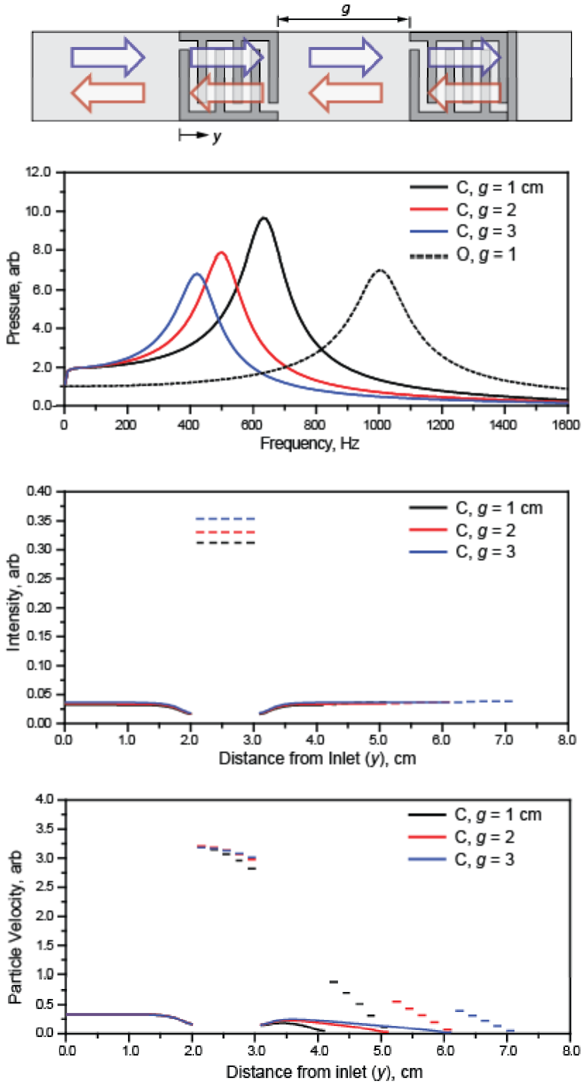
Effective Medium Theory and Reduced Particle Velocity



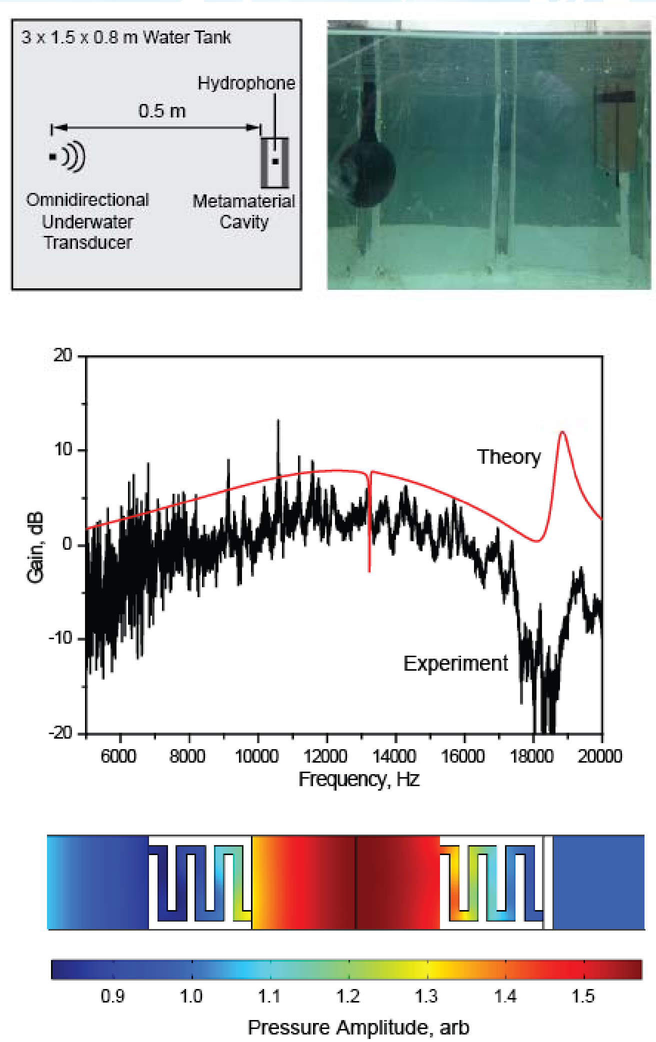
- Effective medium theory exactly replicates the sound pressure amplification results.
- Pressure is increased due to reduced particle velocity ($P = I / c_p$).

Underwater SPL Amplification

Further Enhancement using Quarter Wave Resonator



SPL Amplification in an Underwater Environment



Applications of Acoustic Metamaterial Cavity

Thank You !!