基础物理中心学术活动

# Designing active acoustic metamaterials for manipulating sound

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2. Nonreciprocal intelligent soundproof barrier

3. Acoustic camouflage: walls have ears

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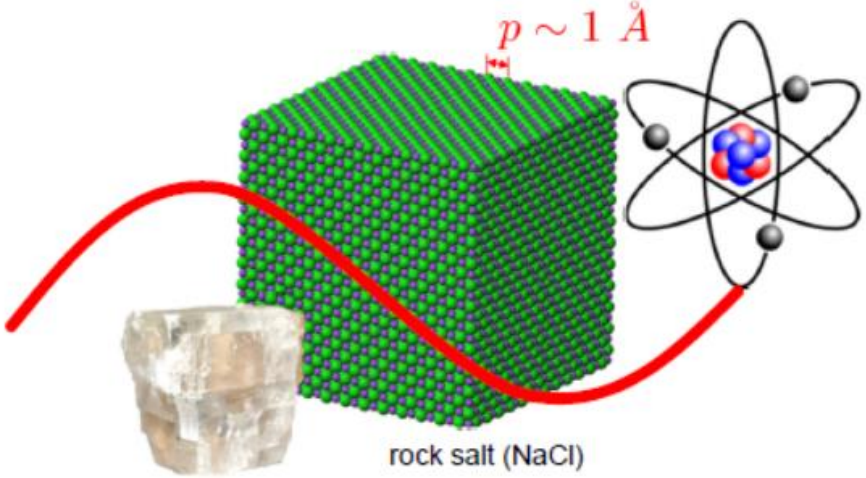
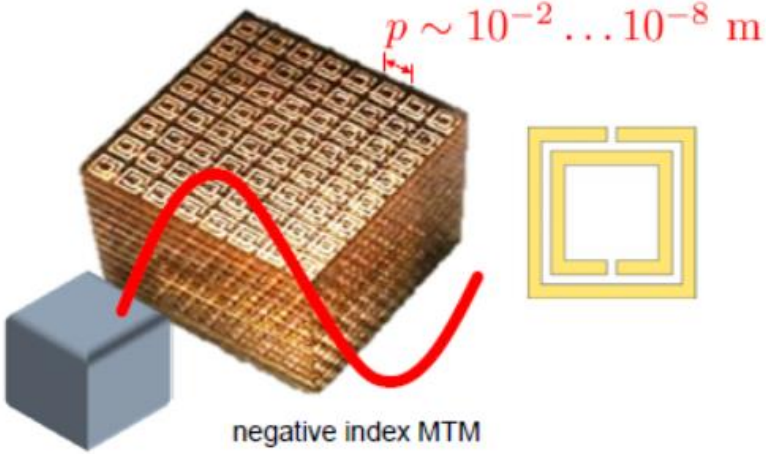
# Background

Natural matter

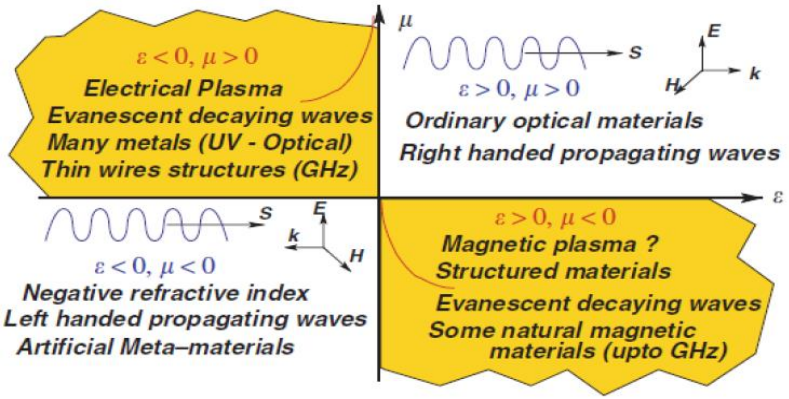



$$p \ll \lambda$$

Metamaterials

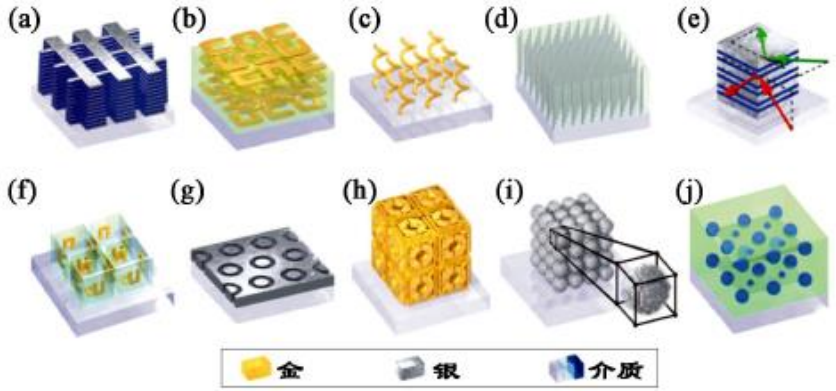



$$\partial_x E_y + \partial_t(\mu H_z) = 0$$
$$\partial_x H_z + \partial_t(\epsilon E_y) = 0$$




Ramakrishna et al. Reports on Progress in Physics, **68**, 449 (2005)

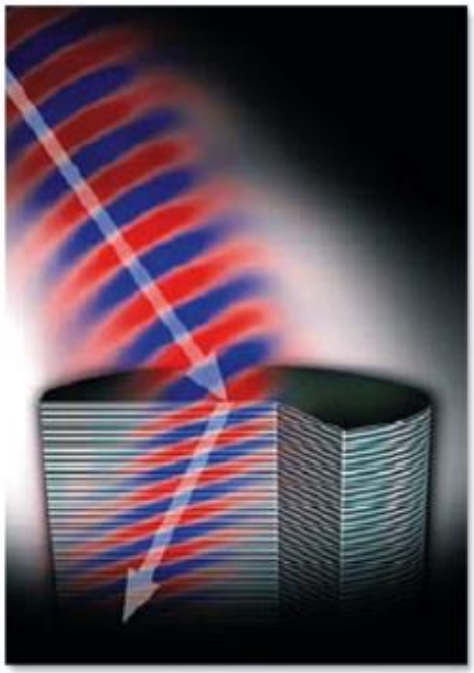
Microstructures for designing metamaterials




Soukoulis et al. Nature Photonics **5,** 523-530 (2011)

# Background

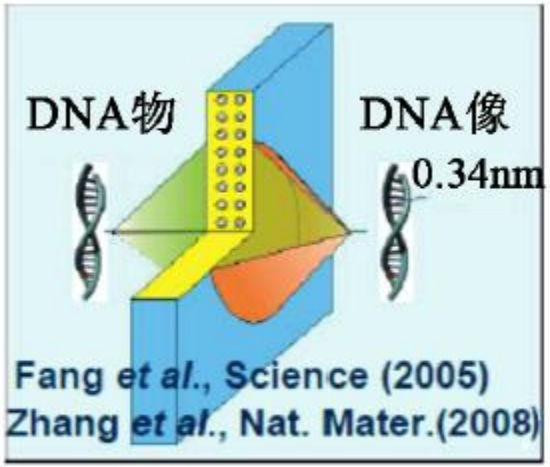
Novel applications based on metamaterials



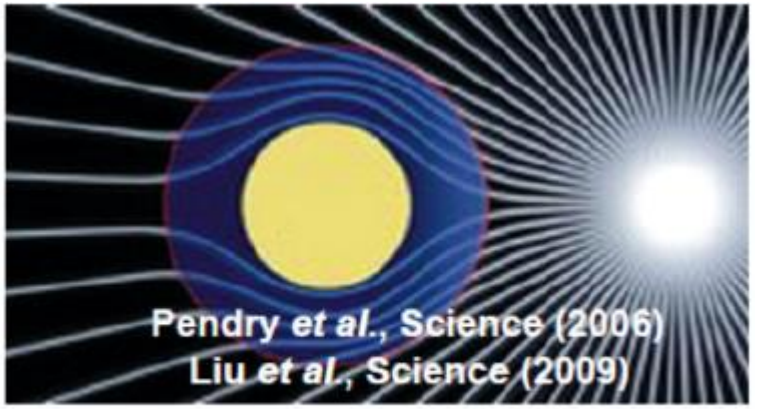
Shelby *et al.*, Science (2001)

Valentine *et al.*, Nature (2008)

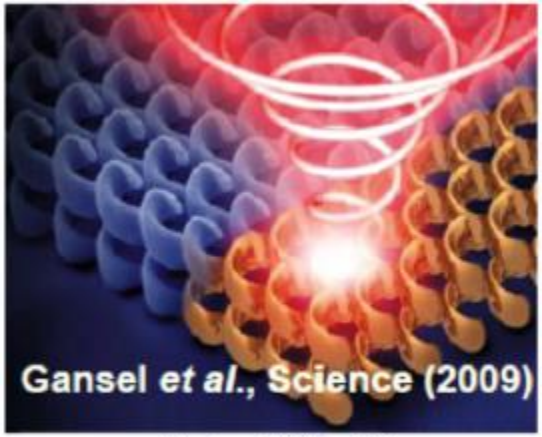
负折射现象



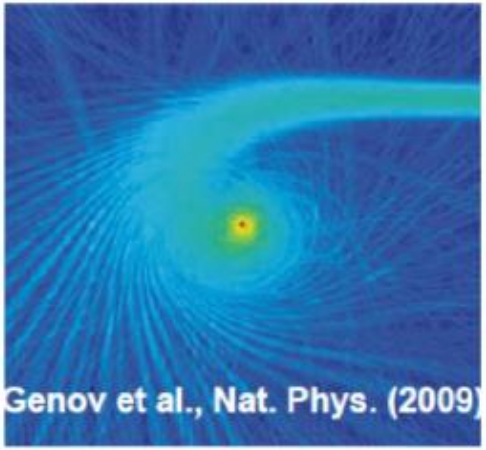

完美成像




电磁隐身




人工旋光

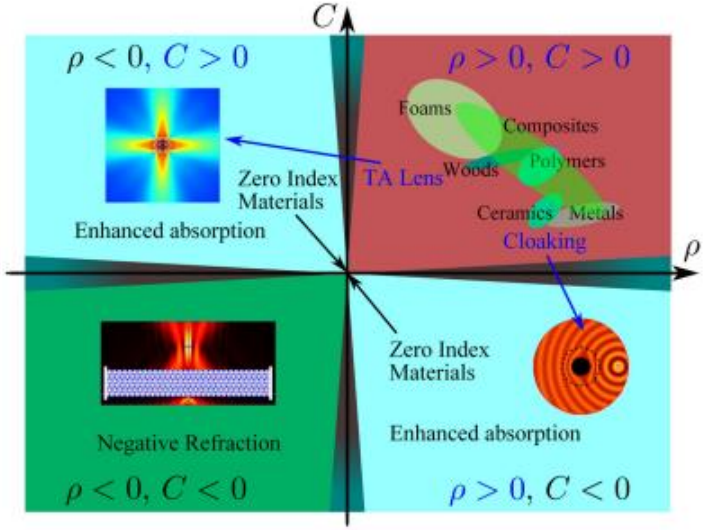



人造黑洞

# Background

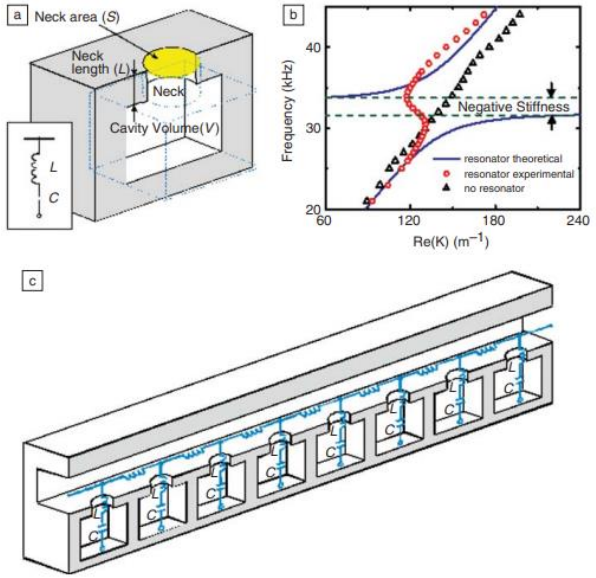
## Constitutive relation

$$\partial_x p + \partial_t(\rho v) = 0$$
$$\partial_x v + \partial_t(\beta p) = 0$$
$$C = \sqrt{1/\beta\rho}$$

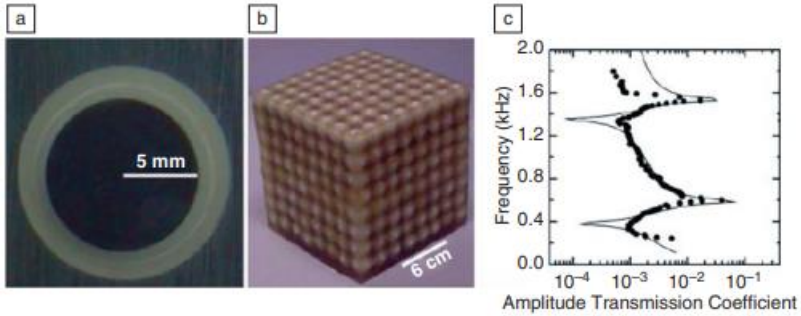



Lee Fok et al. MRS Bulletin, 33, 931 (2008)

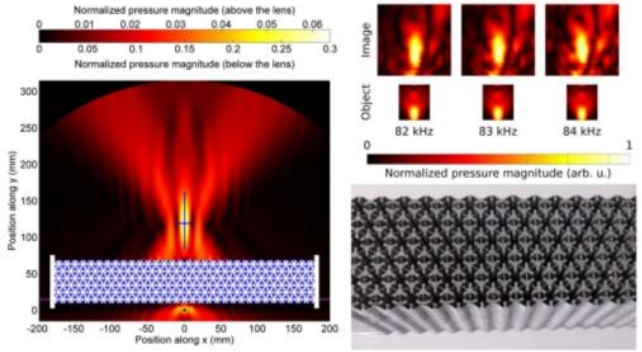
## Negtive-index metamaterials




## Acoustic metamaterials



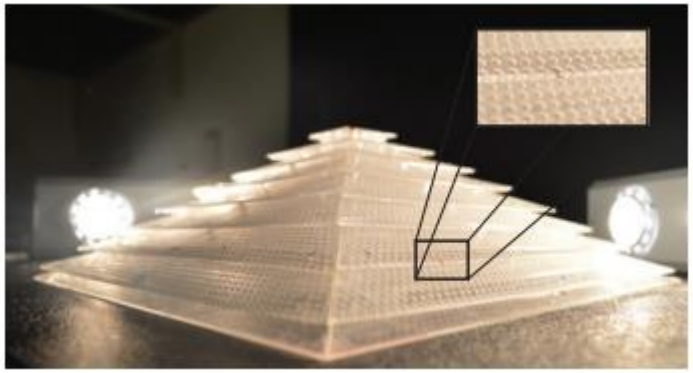

## Acoustic perfect lense

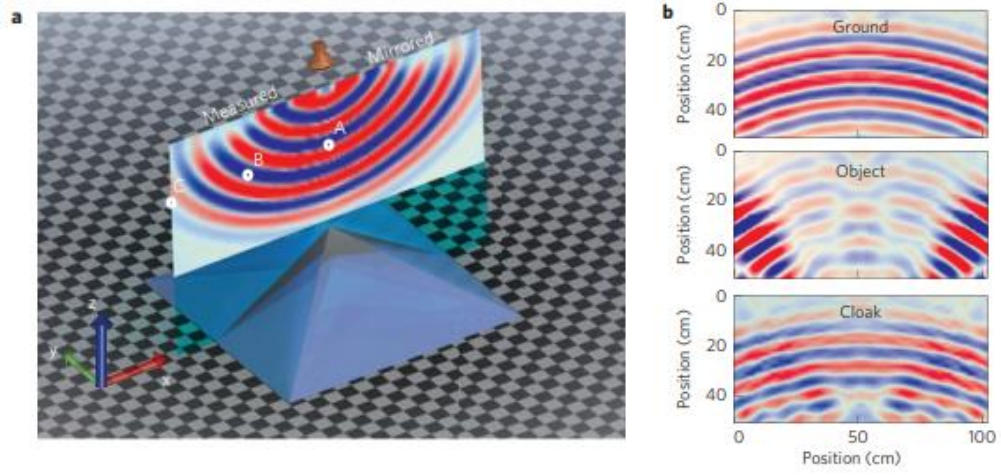



M. R. Haberman, Acoustic Today, 12, 31 (2016)

# Background

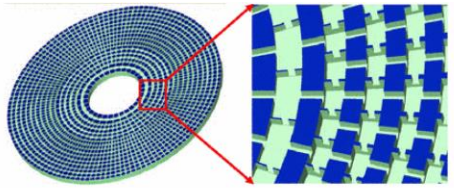
## Acoustic carpet cloaking

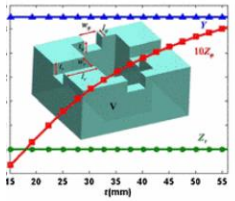





L. Zigoneanu, et al. Nature materials **13**, 352-355 (2014)

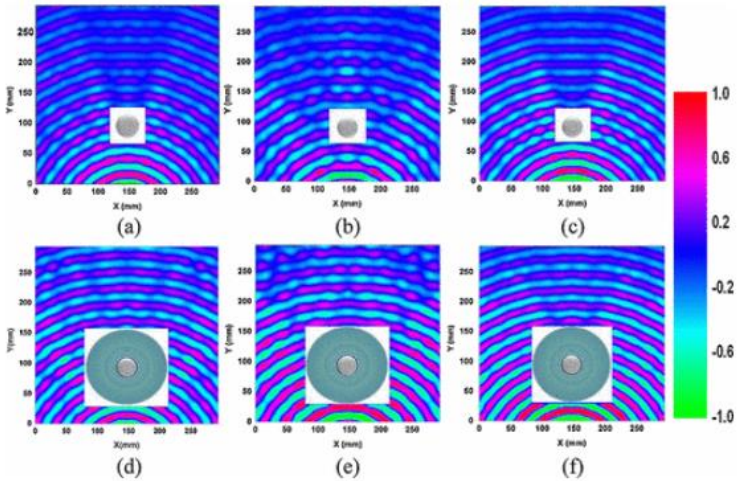
## Acoustic omnidirectional cloaking




| Layer | $l_r$(mm) | $l_\varphi$(mm) | $V$(mm$^3$) |
|---|---|---|---|
| 1 | 2.05 | 0.10 | 3.00 |
| 3 | 1.37 | 0.22 | 2.29 |
| 5 | 1.24 | 0.41 | 2.06 |
| 7 | 1.24 | 0.30 | 2.06 |
| 9 | 1.24 | 0.41 | 2.06 |
| 11 | 1.24 | 0.52 | 2.06 |
| 13 | 1.24 | 0.63 | 2.06 |
| 15 | 1.24 | 0.74 | 2.06 |

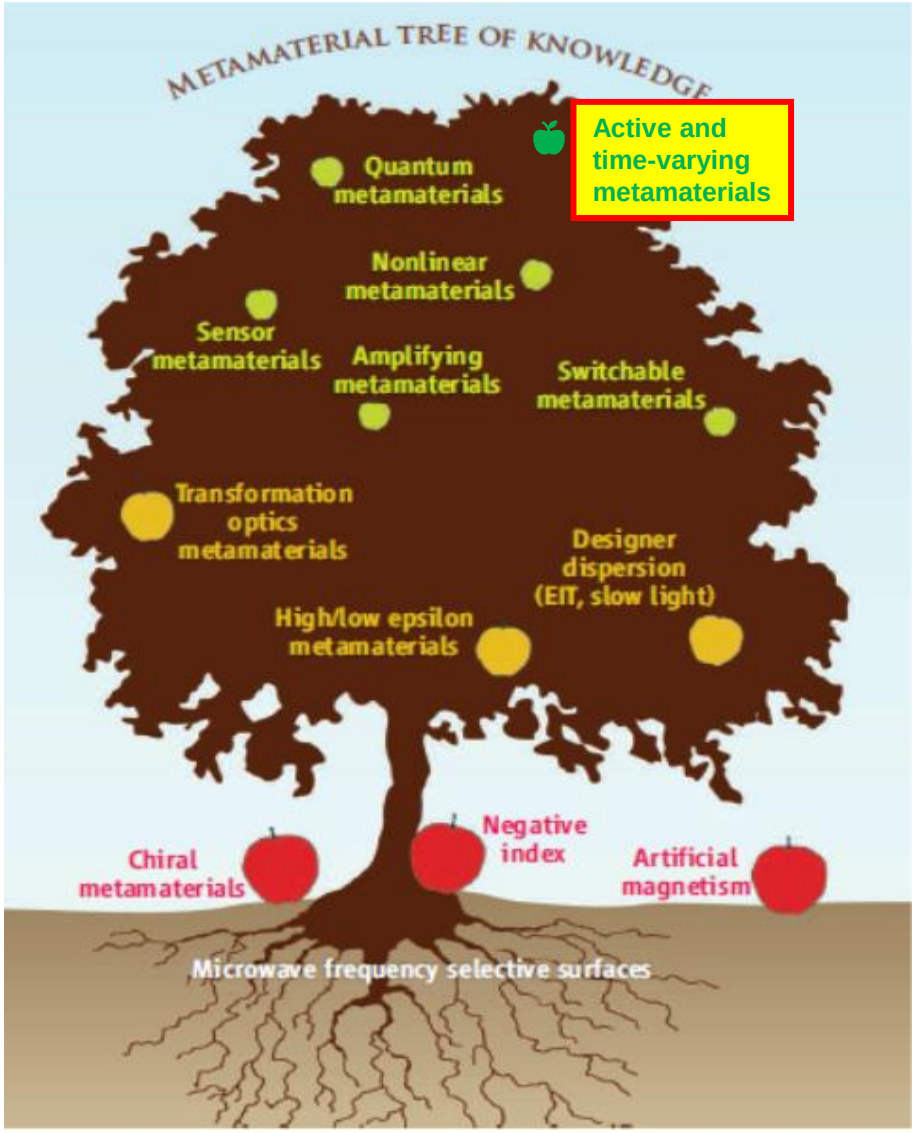
(c)




60kHz 52kHz 64kHz

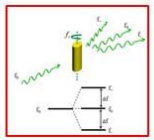
S. Zhang, et al. Phys. Rev. Lett. **106**, 024301(2011)

# Background

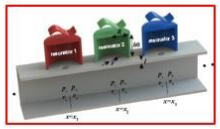

METAMATERIAL TREE OF KNOWLEDGE
Active and time-varying metamaterials
Quantum metamaterials
Nonlinear metamaterials
Sensor metamaterials
Amplifying metamaterials
Switchable metamaterials
Transformation optics metamaterials
Designer dispersion (EIT, slow light)
High/low epsilon metamaterials
Chiral metamaterials
Negative index
Artificial magnetism
Microwave frequency selective surfaces

# Active and time-varying metamaterials

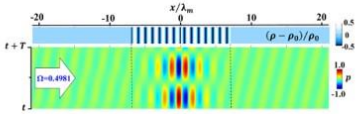
声学时变超材料研究历程



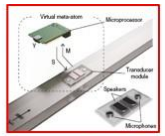
Sci. Rep. **5**, 10880 (2015)
旋转散射体实现
声波不对称传输
◆ 2015年



Phys. Rev. B **99**, 144311 (2019)
Phys. Rev. B **100**, 144311 (2019)
Phys. Rev. B **99**, 134306 (2019)
Phys. Rev. B **102**, 024309 (2020)
转移矩阵理论解析
时空调制声学系统
◆ 2019年

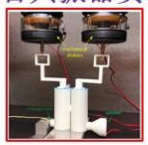


Phys. Rev. Research **1**, 033069 (2019)
理论研究拓扑
时空声子晶体
◆ 2019年



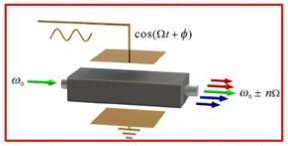
Nat. Commun. **11**, 251 (2020)
提出数字超构原子，模
拟实体共振结构的响应
◆ 2020年

◆ 2019年
时变耦合共振器实现非互易



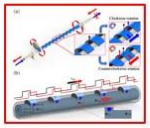
Phys. Rev. B **100**, 054302 (2019)

◆ 2019年
时变波导实现频谱操控




Phys. Rev. Appl. **11**, 064012 (2019)

◆ 2020年
动态边界实现声学pumping

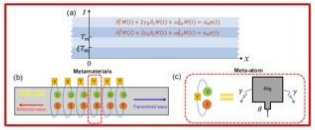


Phys. Rev. Lett. **125**, 253901 (2020)

◆ 2024年
控制声学腔时变耦
合观察Floquet π模

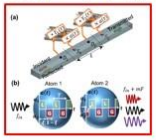
Phys. Rev. B **109**, L020302 (2024)

◆ 2023年
系统研究色散、非色散时变
超构材料的等效媒质理论



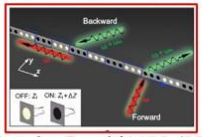
Phys. Rev. B.108. 104303 (2023)

◆ 2022年
提出非厄米时变人工原
子，实现声单向放大



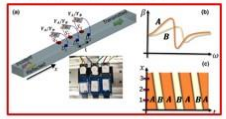
Commun. Phys. **5**, 18 (2022)

◆ 2021年
控制扬声器阻抗实
现非互易模式转换




Sci. Adv. **7**, eabj1198 (2021)

◆ 2021年
时变超构材料在时变共振
强度时的等效媒质理论



Phys. Rev. B.104. L060304 (2021)

# Nonreciprocal intelligent soundproof barrier

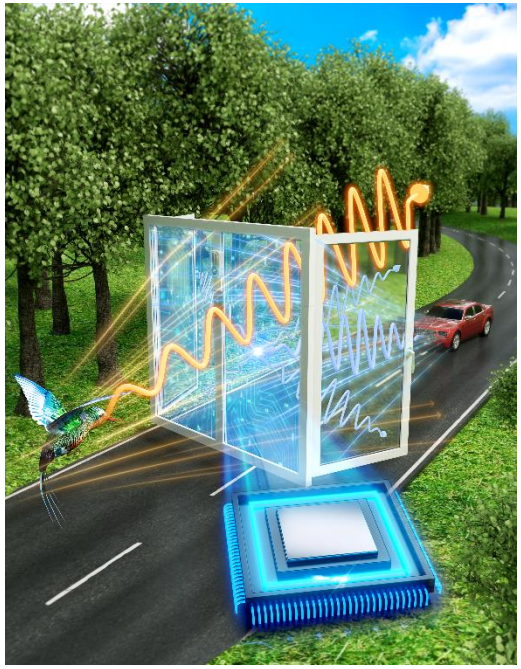
RESEARCH ARTICLE

ADVANCED MATERIALS TECHNOLOGIES

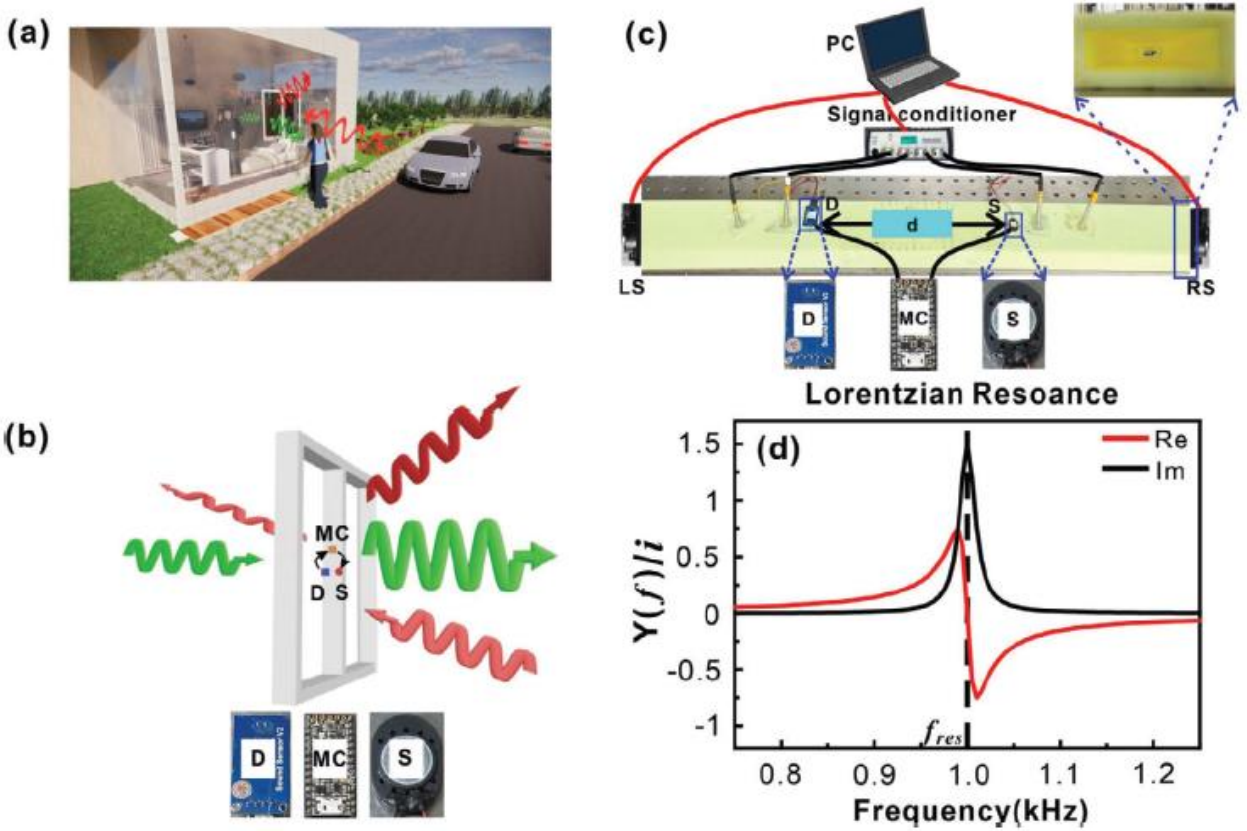
www.advmattechnol.de

## Nonreciprocal Intelligent Soundproof Barrier with Active Nonlocal Acoustic Metastructure

*Yue Zhuo, Xue Chen,* Ziling Liu, Zong-Qiang Sheng, and Hong-Wei Wu**



# Nonreciprocal intelligent soundproof barrier




Response function $Y(f) \cong \frac{g}{2}\left(\frac{e^{i\theta'}}{\omega_{\text{res}} + \omega + i\gamma} + \frac{e^{-i\theta'}}{\omega_{\text{res}} - \omega - i\gamma}\right)$

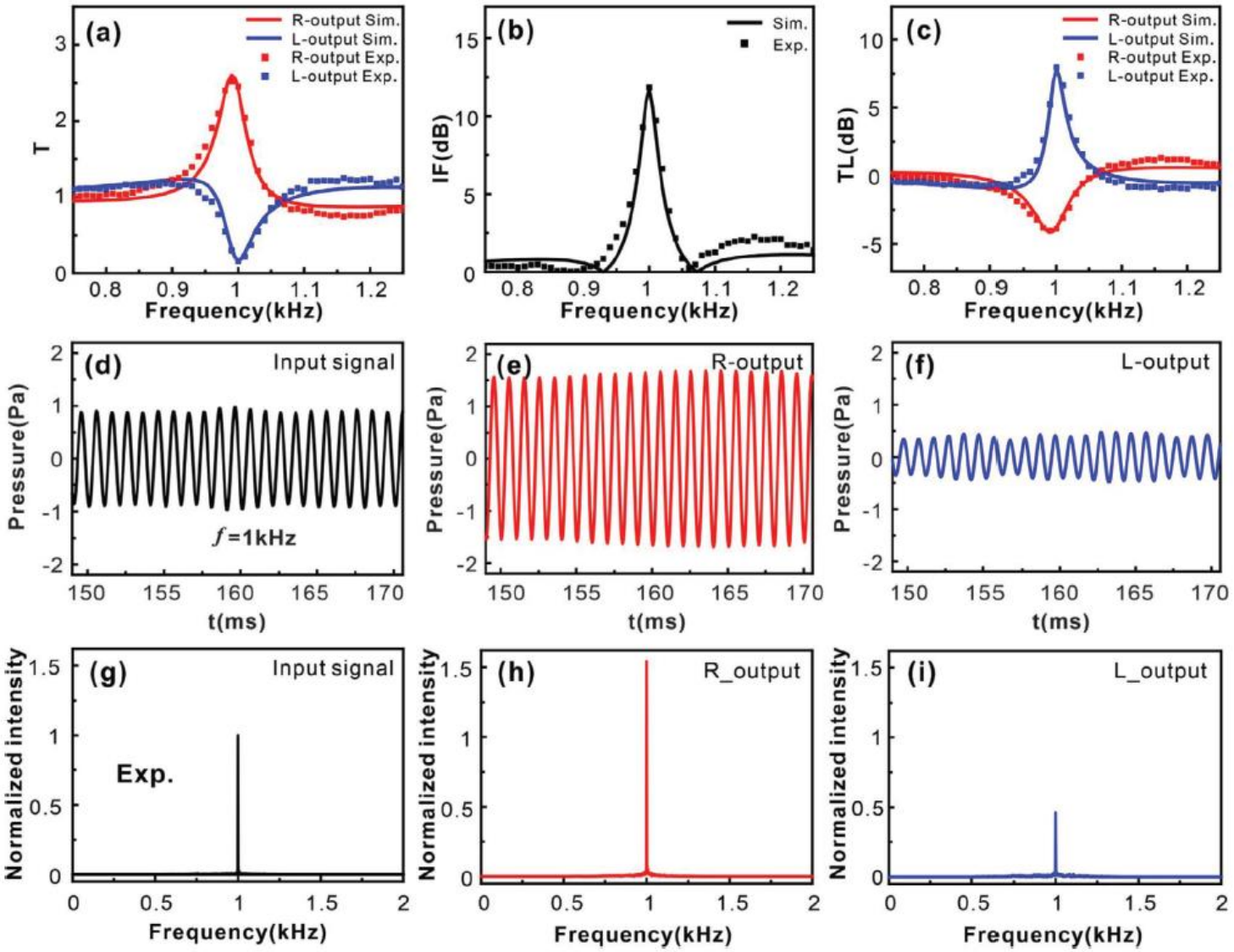
Nonreciprocal factor $\phi = k\,d$

Transmissivity and Reflective:

$$t_R(f) = \frac{1 + Y(f)\,e^{-i\phi} - Y(f)\,e^{i\phi}}{1 - Y(f)\,e^{i\phi}}$$

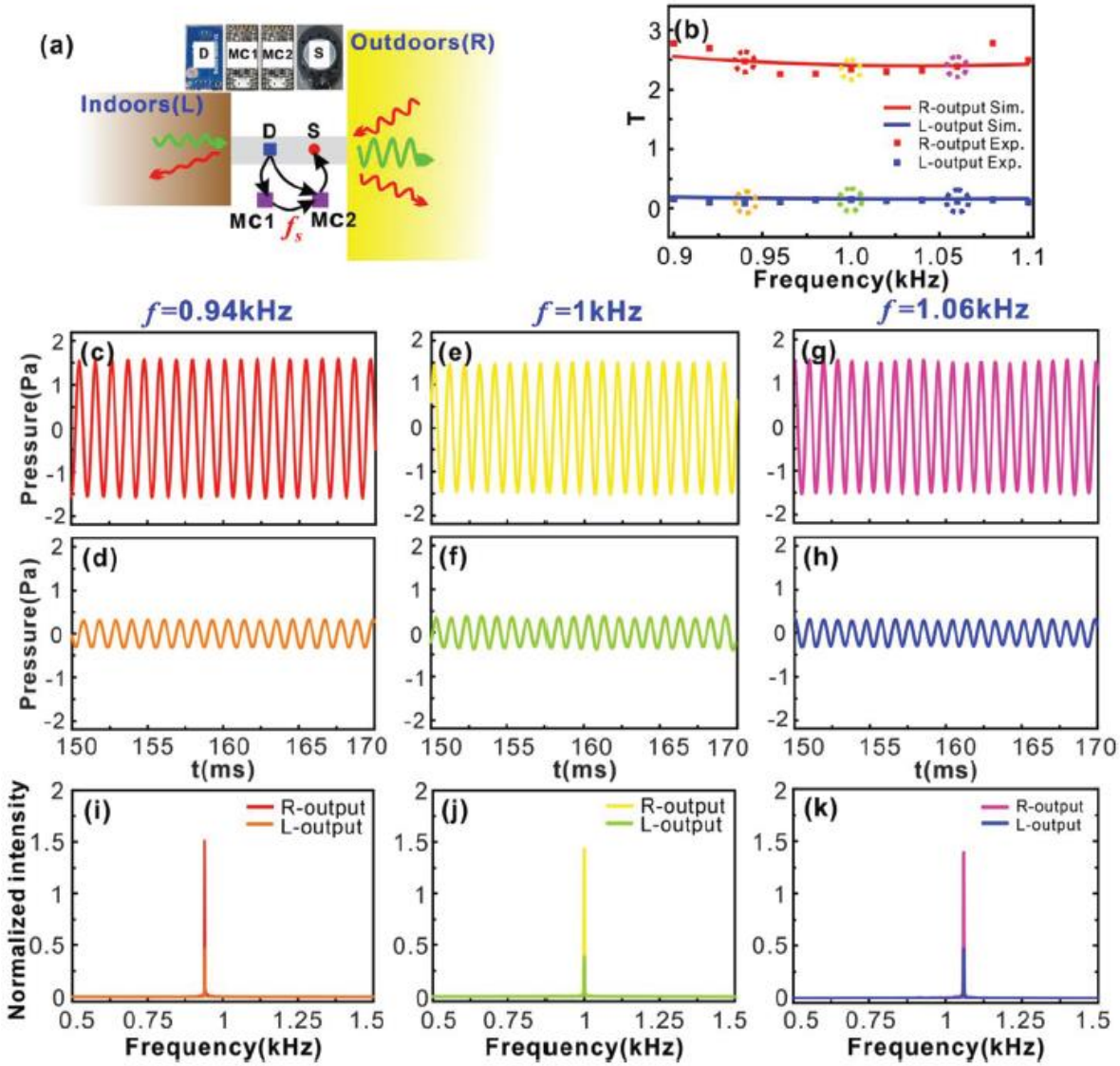
$$t_L(f) = \frac{1 + Y(f)\,e^{i\phi} - Y(f)\,e^{i\phi}}{1 - Y(f)\,e^{i\phi}}$$

# Nonreciprocal intelligent soundproof barrier



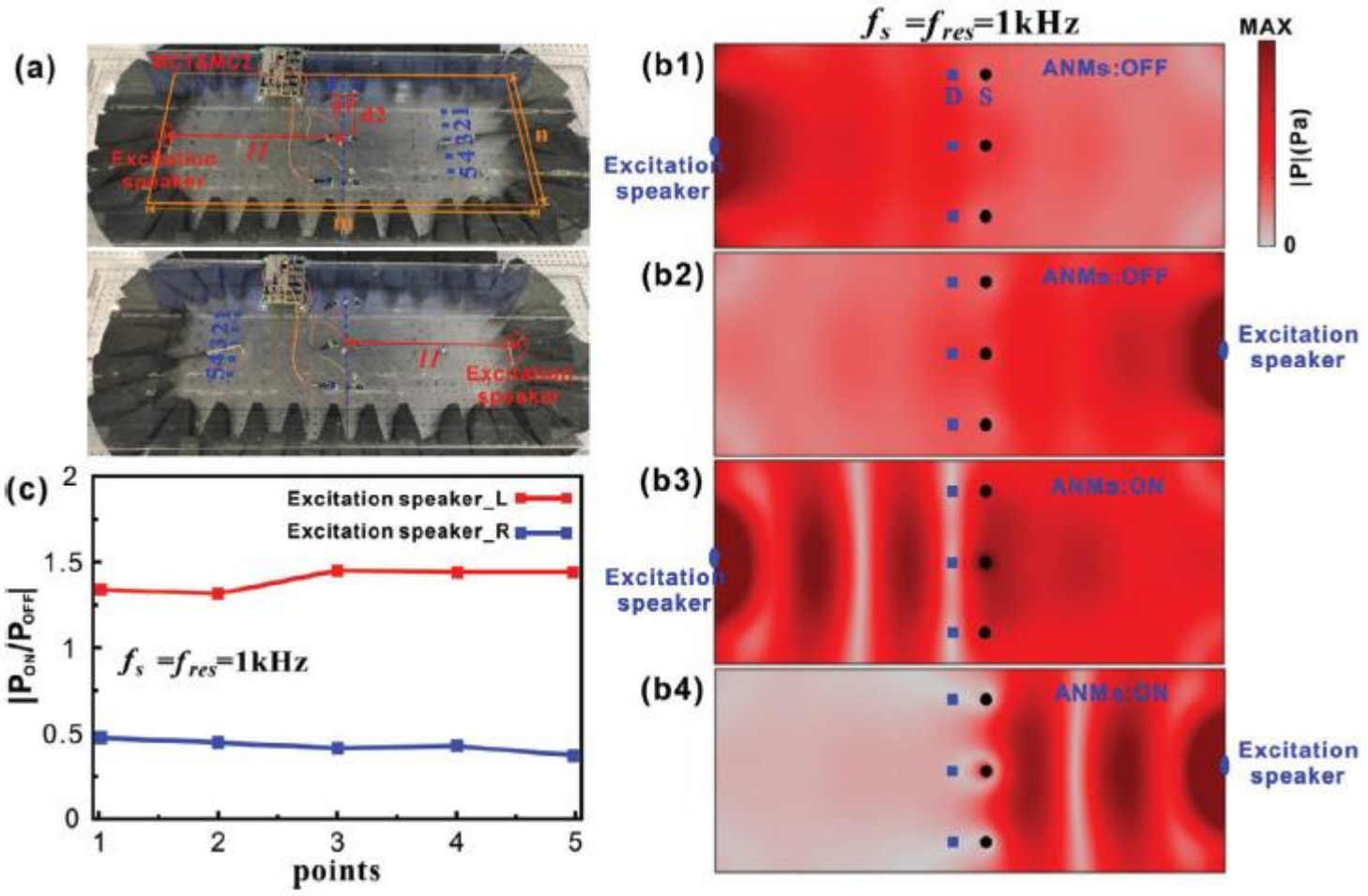
# Nonreciprocal intelligent soundproof barrier

Frequency-tunable soundproof barrier

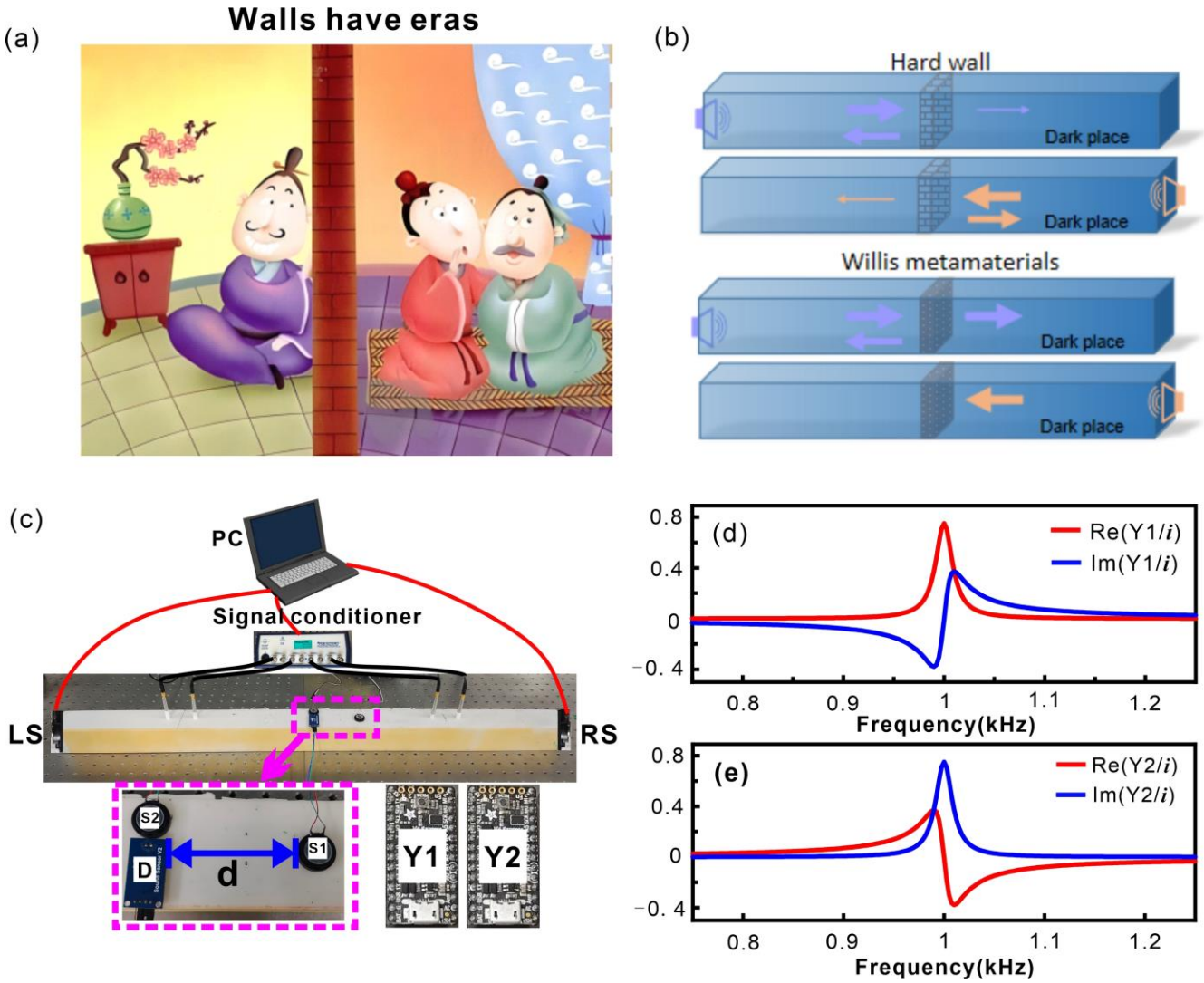


# Nonreciprocal intelligent soundproof barrier

2D soundproof barrier



# Acoustic camouflage: walls have ears




Manuscript preparation

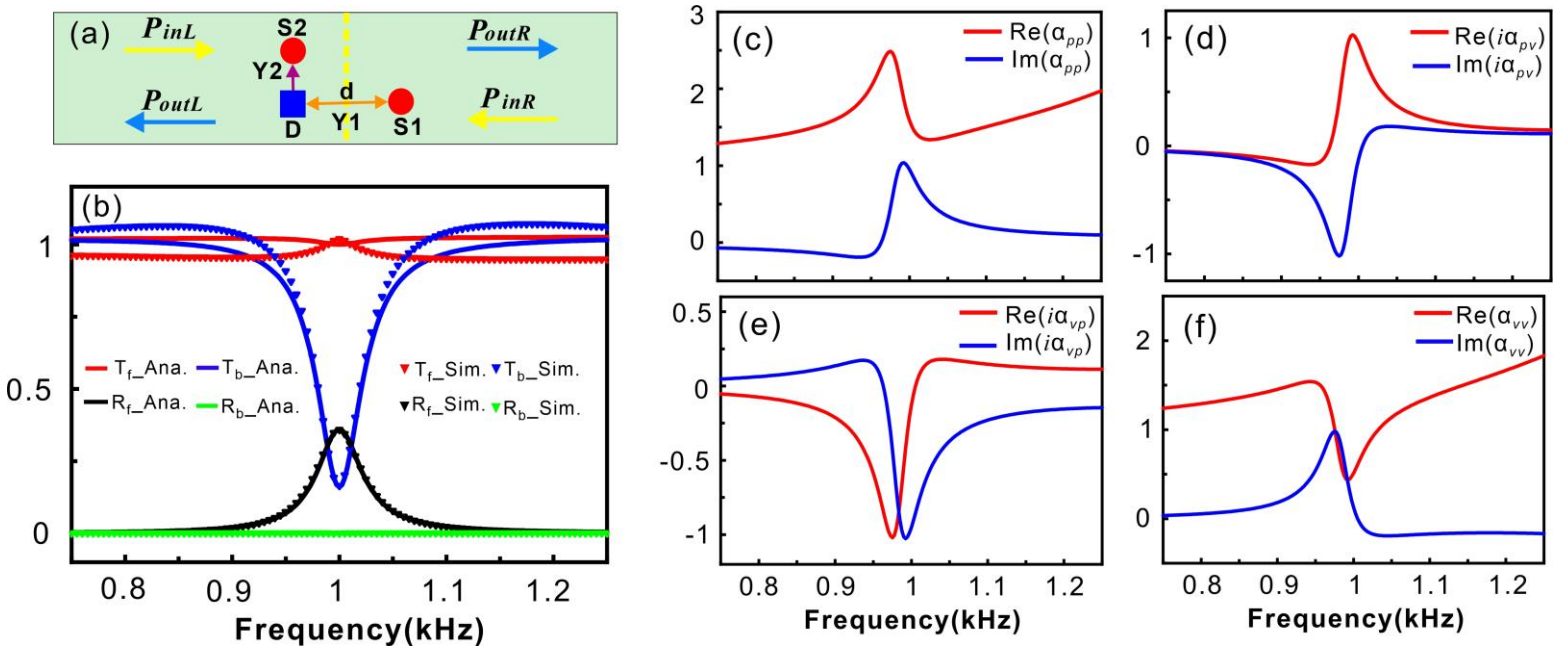
# Acoustic camouflage: walls have ears

Constitutive relation of electromagnetic bi-anisotropy metamaterials

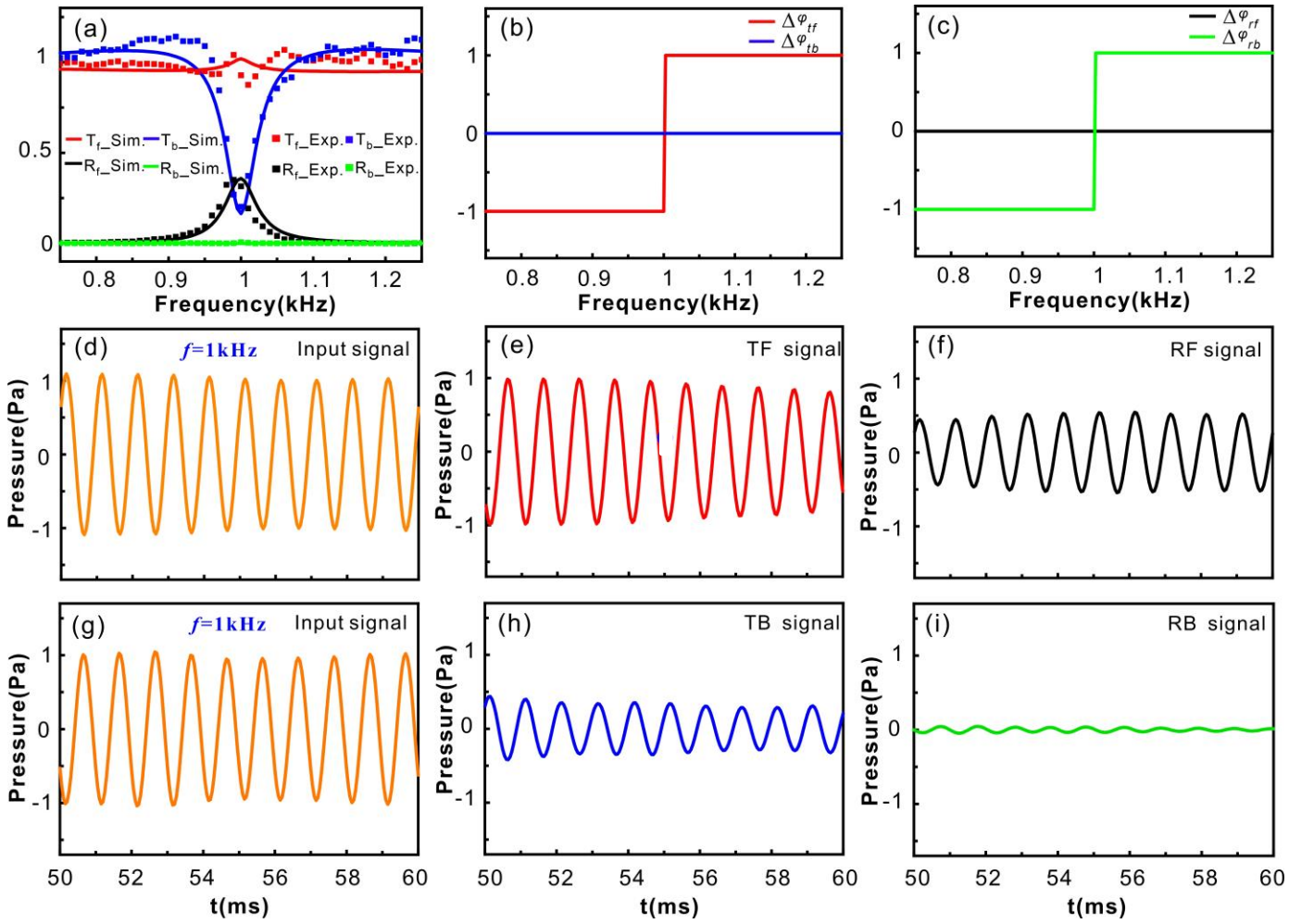
$$\begin{pmatrix} D \\ B \end{pmatrix} = \begin{pmatrix} \chi_{ee} & \chi_{em} \\ \chi_{me} & \chi_{mm} \end{pmatrix} \begin{pmatrix} E \\ H \end{pmatrix}$$

Constitutive relation of acoustic Willis metamaterials

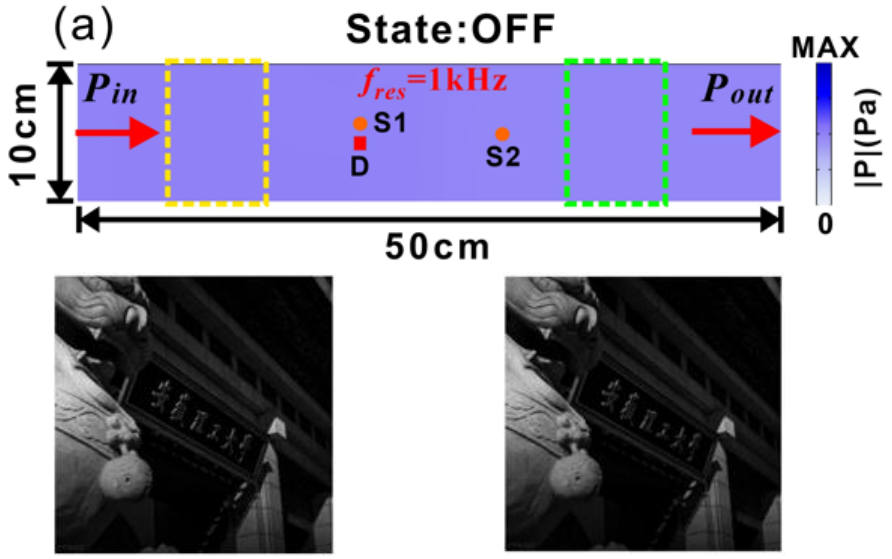
$$\begin{pmatrix} M \\ D \end{pmatrix} = \begin{pmatrix} \alpha_{pp} & \alpha_{pv} \\ \alpha_{vp} & \alpha_{vv} \end{pmatrix} \begin{pmatrix} p \\ v \end{pmatrix}$$

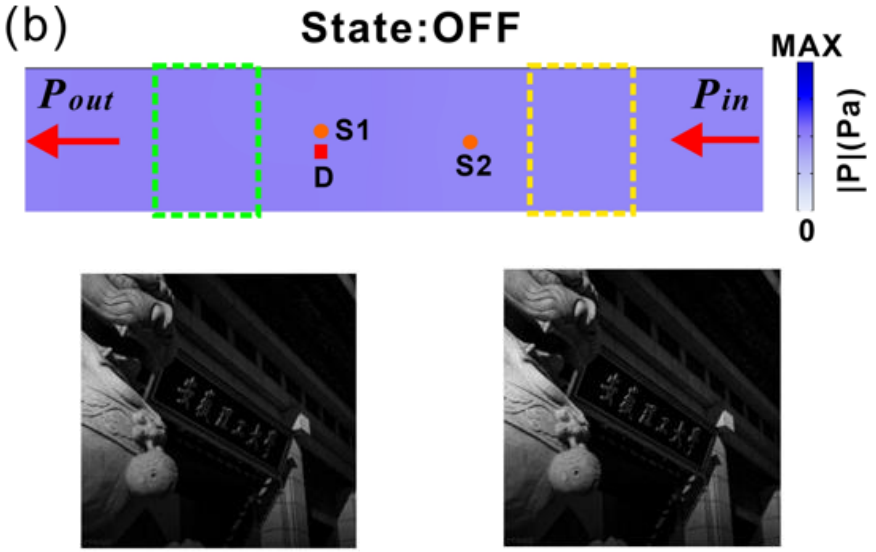


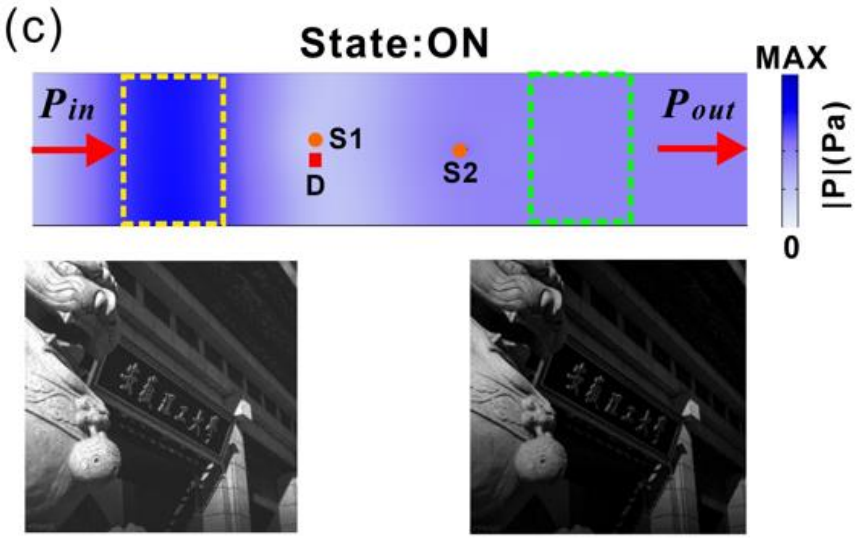
# Acoustic camouflage: walls have ears

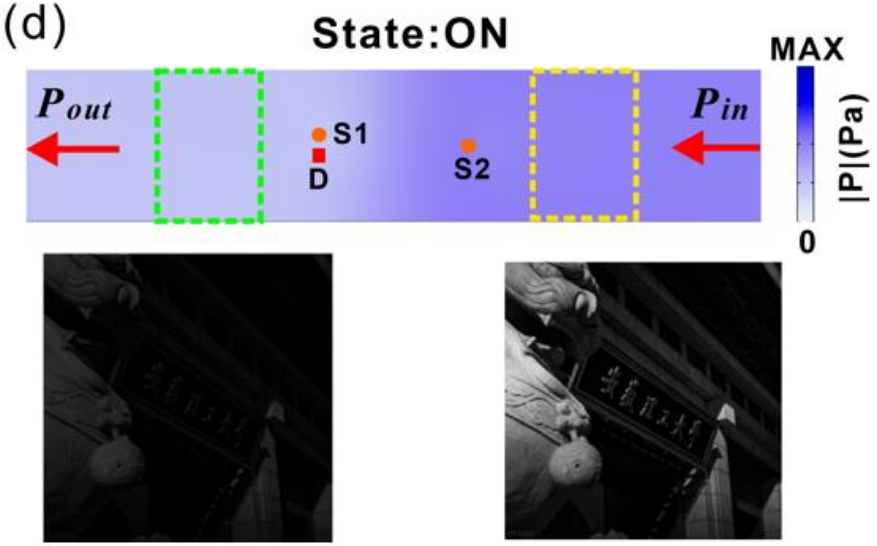


# Acoustic camouflage: walls have ears



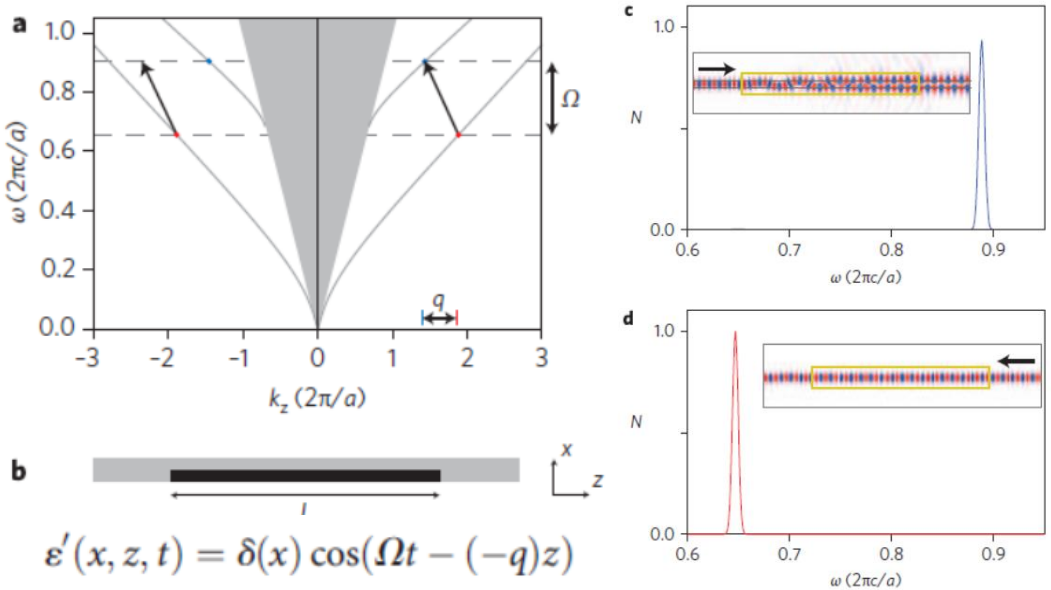



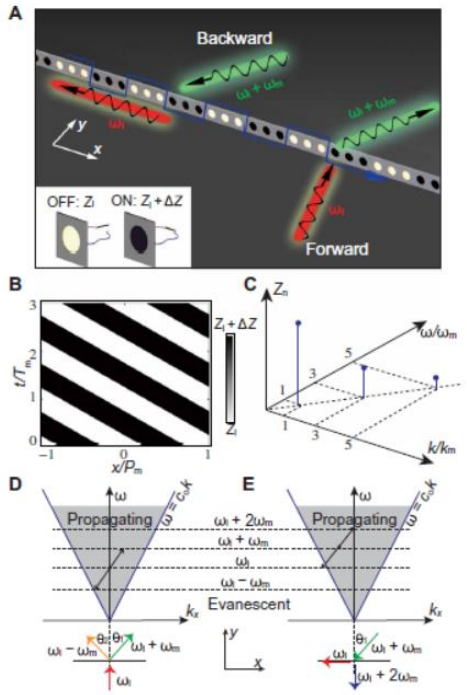



# Acoustic time-varying metamaterials

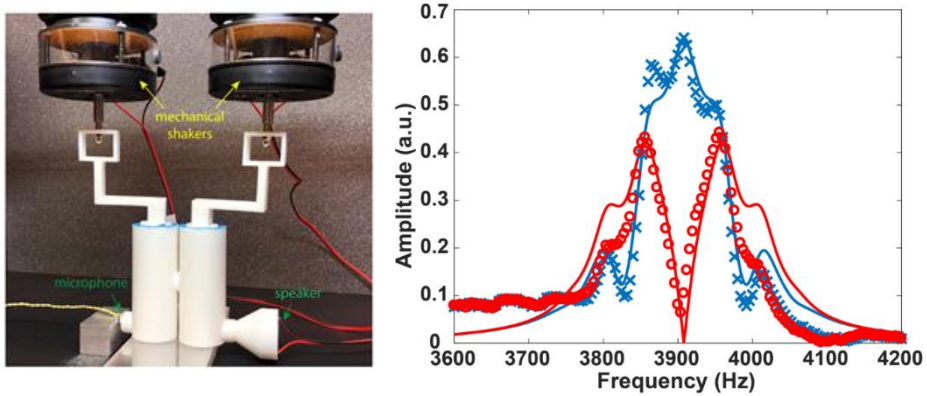
## Non-reciprocal transmission



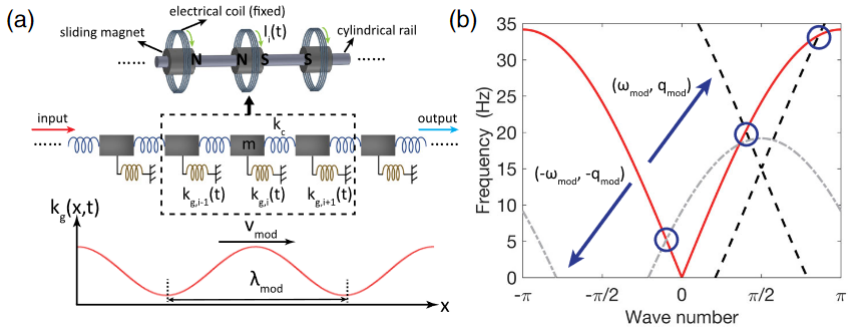

Nature Photonics **3,** 91 (2009)




Science Advances **7**, eabj1198 (2021)



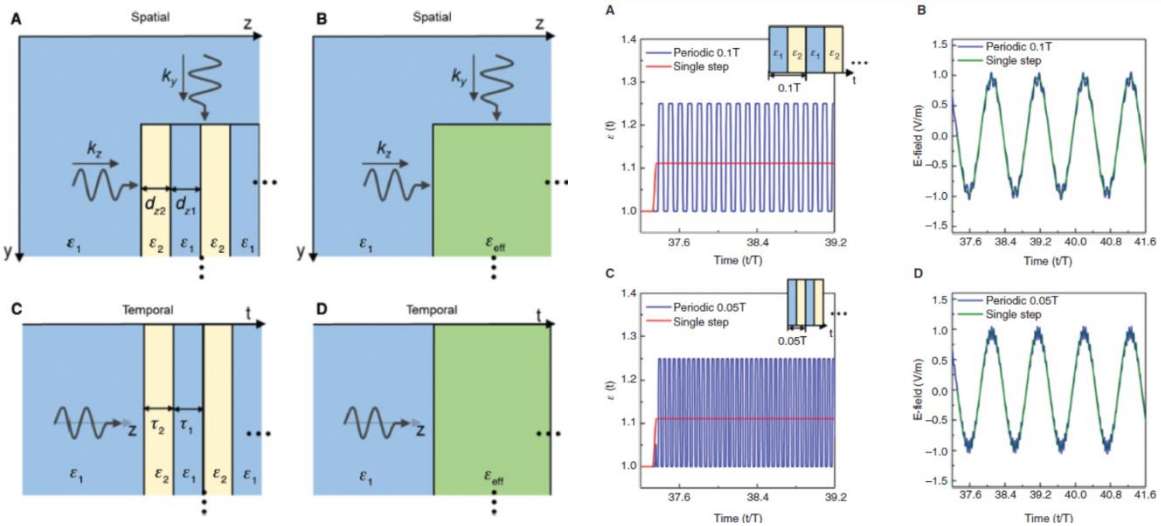

Physical Review B **100**, 054302 (2019)




Physical Review Letters **121**, 194301 (2018)

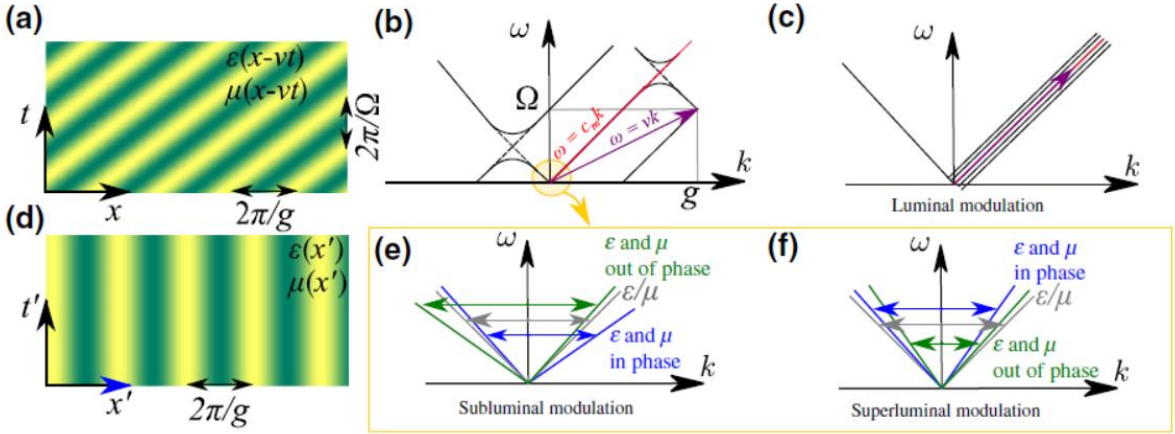
# Acoustic time-varying metamaterials

Effective medium concept in temporal metamaterials




Nanophotonics **9**, 379 (2020)

Homogenization Theory of Space-Time Metamaterials

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# Acoustic time-varying metamaterials

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## Effective medium for time-varying frequency-dispersive acoustic metamaterials

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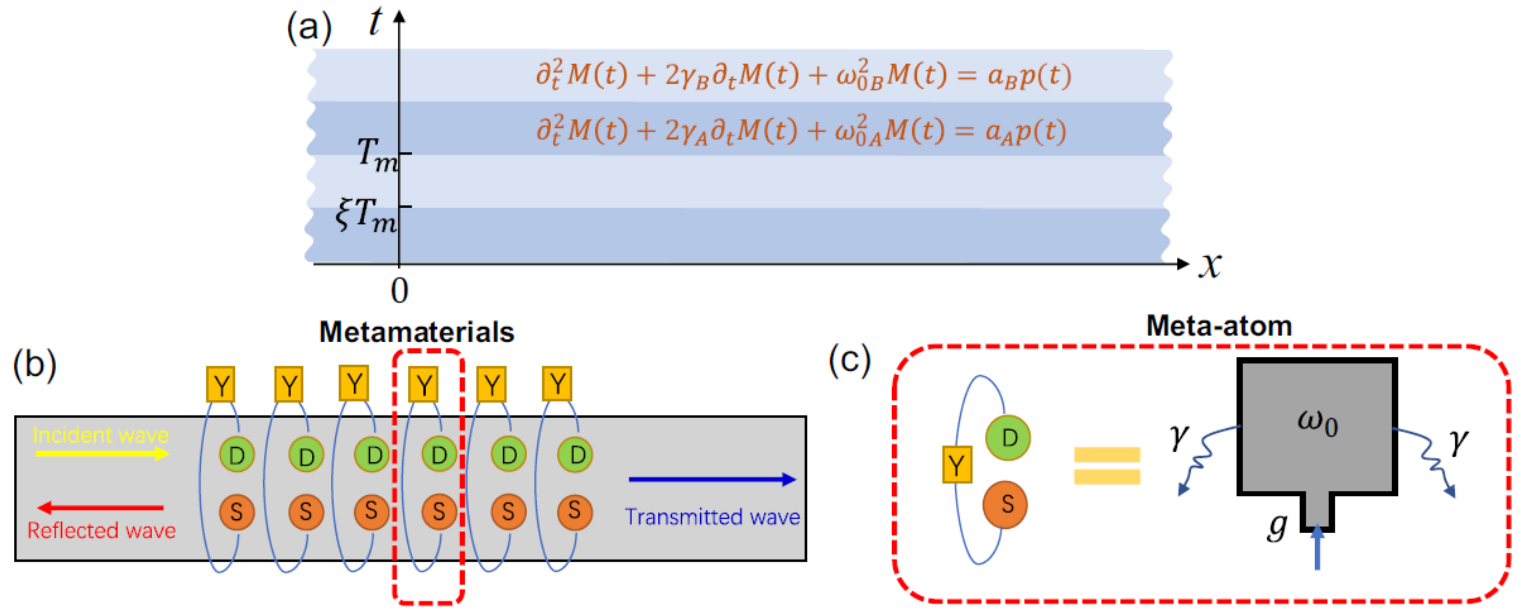
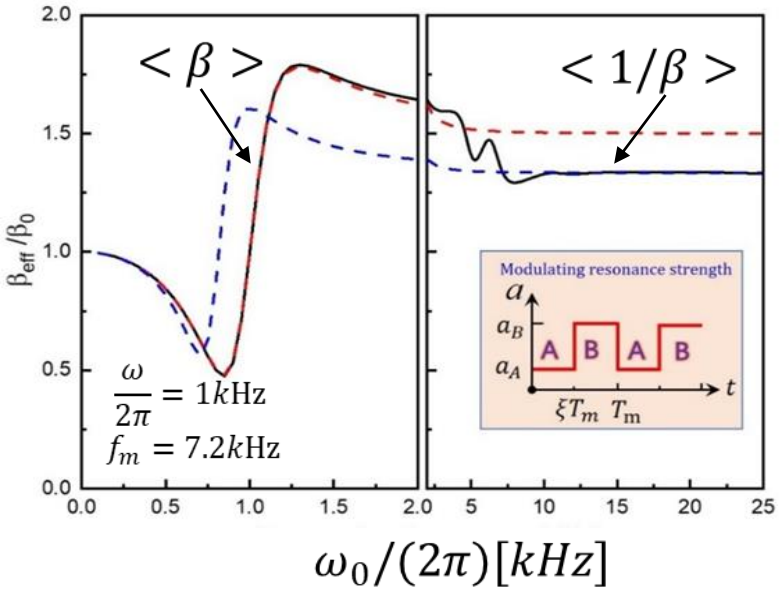


# Acoustic time-varying metamaterials

$$\partial_x p(x,t) + \rho_0 \partial_t v(x,t) = 0$$
$$\partial_x v(x,t) + \beta_0 \partial_t ( p(x,t) + M(x,t) ) = 0$$
$$\partial_t^2 M(x,t) + 2\gamma(t)\partial_t M(x,t) + \omega_0^2(t) M(x,t) = a(t) p(x,t)$$

$$i\partial_t \psi = \hat{\omega}\psi, \ \psi = (p, v, M, -\partial_t M)^T$$

$$\hat{\omega} = \begin{pmatrix} 0 & \frac{k}{\beta_0} & 0 & i \\ \frac{k}{\rho_0} & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ -ia(t) & 0 & i\omega_0^2 & -i2\gamma \end{pmatrix}$$




Eigen-mode

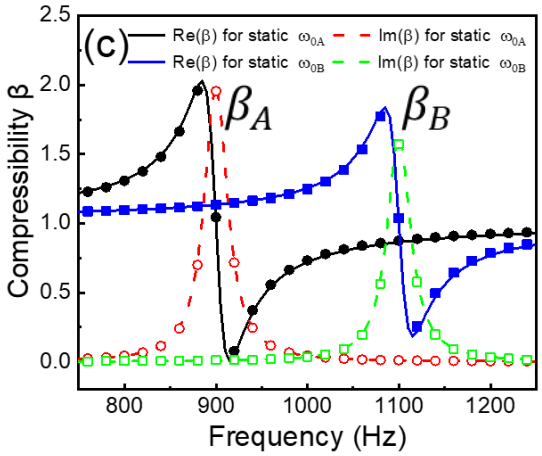
$$\frac{\rho_{\text{eff}}}{\rho_0} = \frac{k}{\omega\beta_0}\frac{v}{p+M},$$
$$\frac{\beta_{\text{eff}}}{\beta_0} = \frac{k}{\omega\rho_0}\frac{p+M}{v}.$$

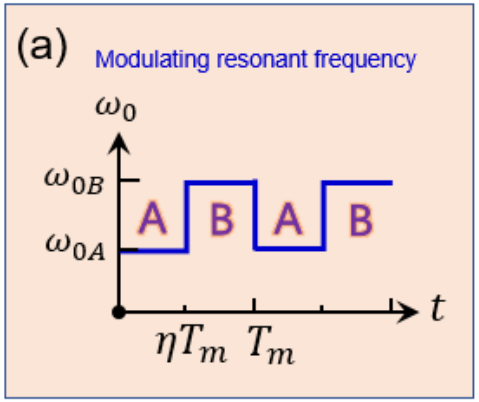
increase $\omega_0$

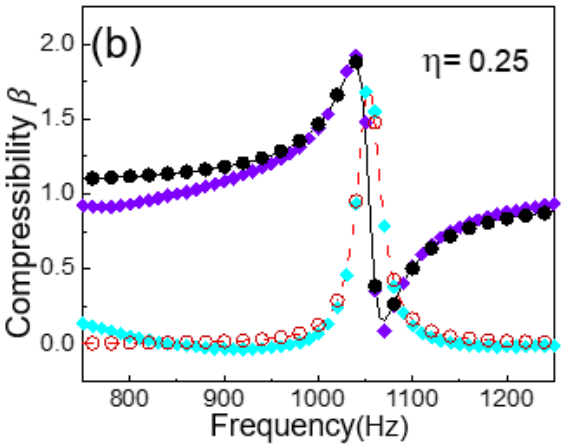
$\beta_{\text{eff}} = \xi\beta_A + (1-\xi)\beta_B$ → $1/\beta_{\text{eff}} = \xi/\beta_A + (1-\xi)/\beta_B$

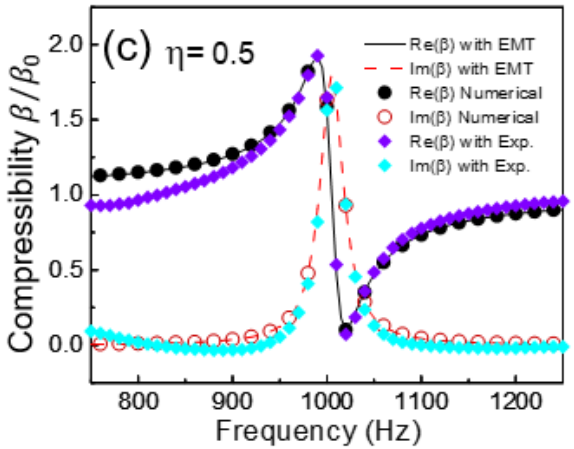
dispersive → nondispersive

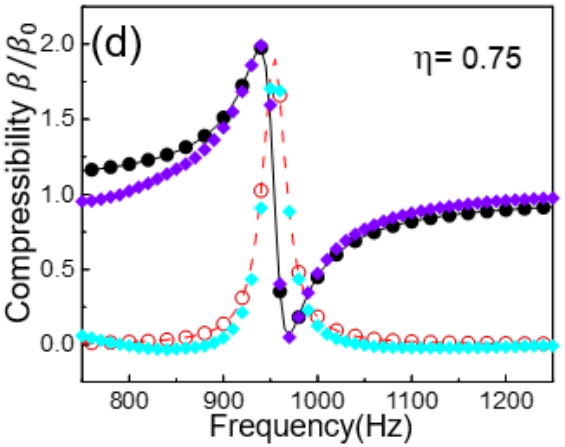
# Acoustic time-varying metamaterials




$$\frac{1}{\beta_{\mathrm{eff}}(\omega)-1}=\frac{\eta}{\beta_{\mathrm{A}}(\omega)-1}+\frac{1-\eta}{\beta_{\mathrm{B}}(\omega)-1}$$

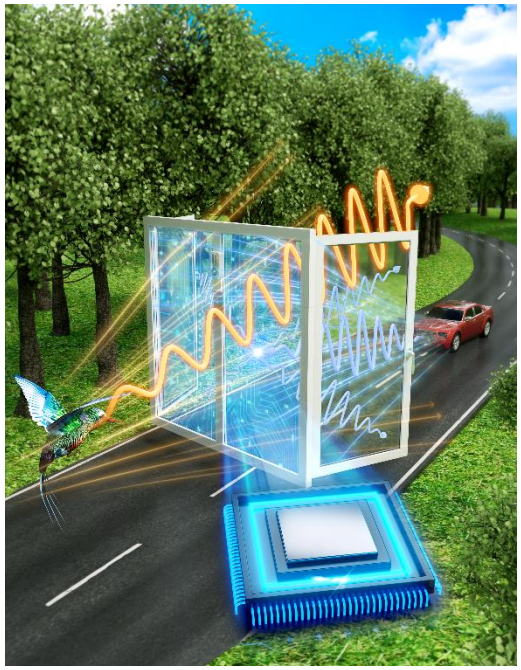
# Acoustic time-varying metamaterials

Equivalent medium algorithm:

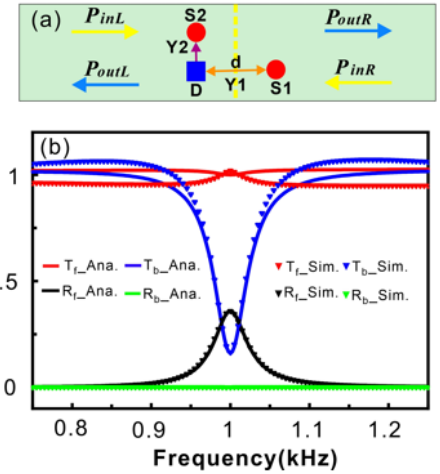
| Modulating Parameters | Average $\beta$ | Average $1/(\beta-1)$ | Average $1/\beta$ |
|---|---|---|---|
| Resonant strength $a$ | ✓ | | |
| Resonant frequency $\omega_0$ | | ✓ | |
| Decay rate $\gamma$ | | ✓ | |
| Resonant strength $a(\omega_0$ large ) | | | ✓ |

# Conclusion

## 1. Acoustic time-varying metamaterials



## 2. Acoustic camouflage




## 3. Establishing temporal effective medium formula

$$\beta_{\text{eff}} = \xi\beta_A + (1-\xi)\beta_B$$

$$1/\beta_{\text{eff}} = \xi/\beta_A + (1-\xi)/\beta_B$$

$$\frac{1}{\beta_{\text{eff}}(\omega)-1} = \frac{\eta}{\beta_{\text{A}}(\omega)-1} + \frac{1-\eta}{\beta_{\text{B}}(\omega)-1}$$

***Thank you!***