SAND2019-2334C

Achieving structural vibration isolation via a total-internal-reflection elastic metasurface

Hongfei Zhu[1], Timothy F. Walsh[2] and Fabio Semperlotti[1]

[1]Ray W. Herrick Laboratories
School of Mechanical Engineering
Purdue University

[2] Sandia National Laboratories

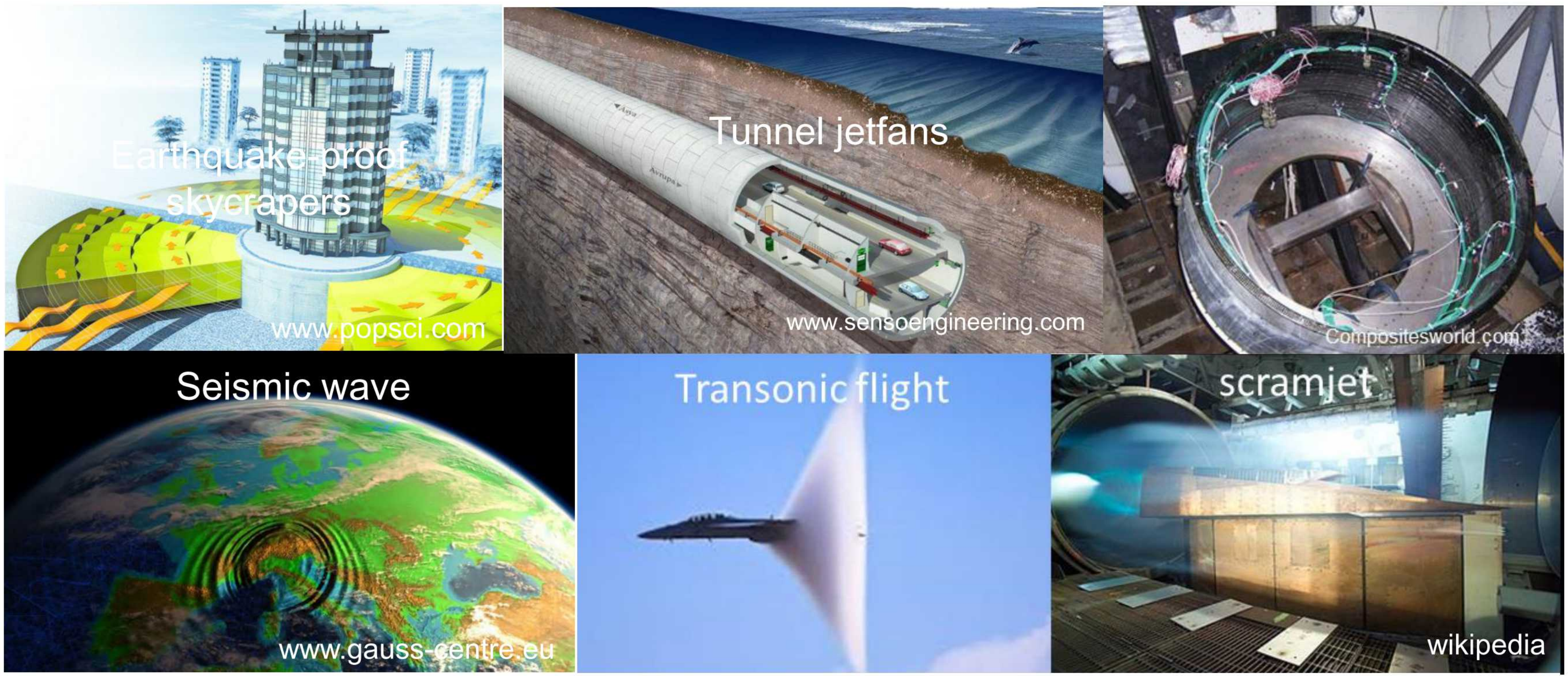
Outline

- **Introduction and motivations**
- **Total-internal-reflection metasurface**
  - ✓ Generalized Snell's law
  - ✓ Phase gradient design
- **Analytical and numerical study**
  - ✓ Flat and circular TIR-MS
  - ✓ Performance assessment
- **Experimental validation**
- **Conclusions**

Background and motivations:

Vibrations isolation

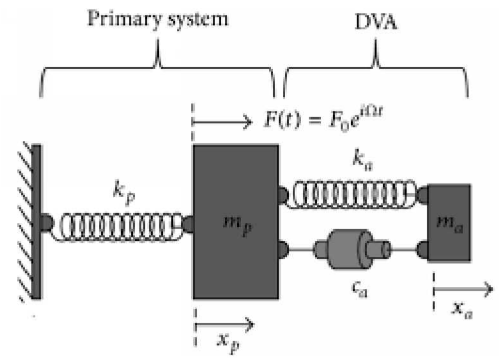
Subwavelength vibrations isolation has been a long standing challenge in structural dynamics.

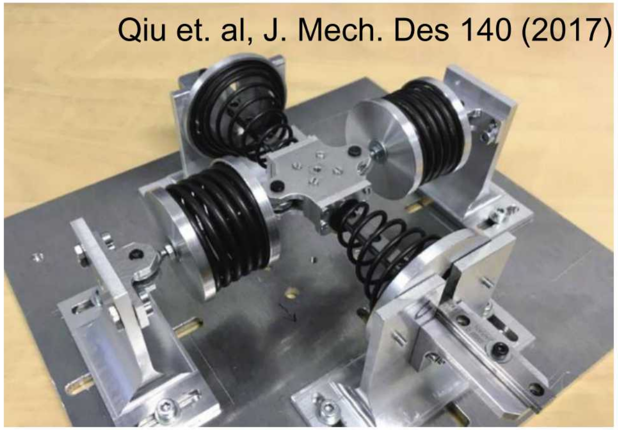


Background and motivations:

Vibrations isolation

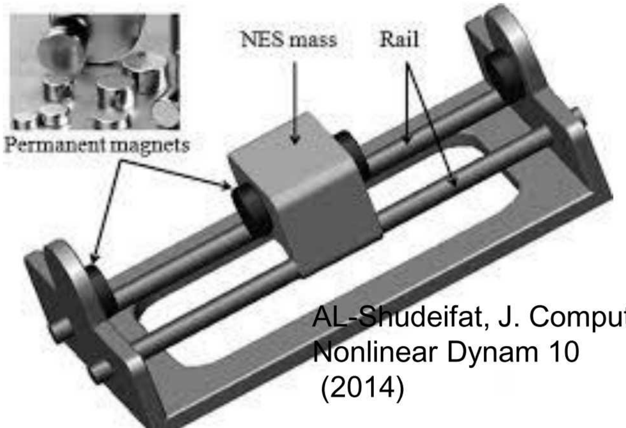
Typical approaches have relied on vibration absorbers either linear or nonlinear.





Qiu et. al, J. Mech. Des 140 (2017)

https://www.wixroyd.com



AL-Shudeifat, J. Comput. Nonlinear Dynam 10 (2014)

Nonlinear energy sink

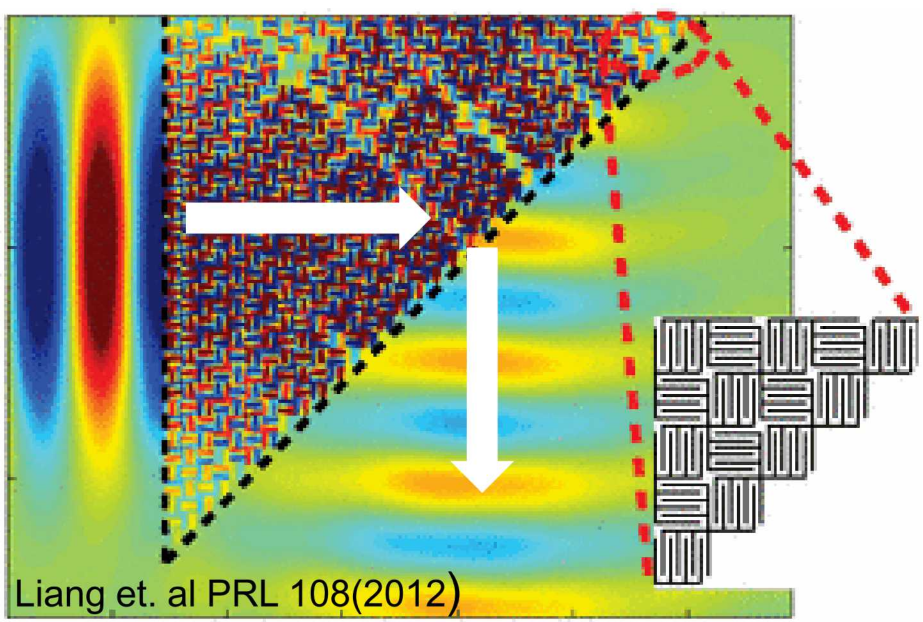
Drawback: cannot effectively isolate from wavefronts

Background and motivations:

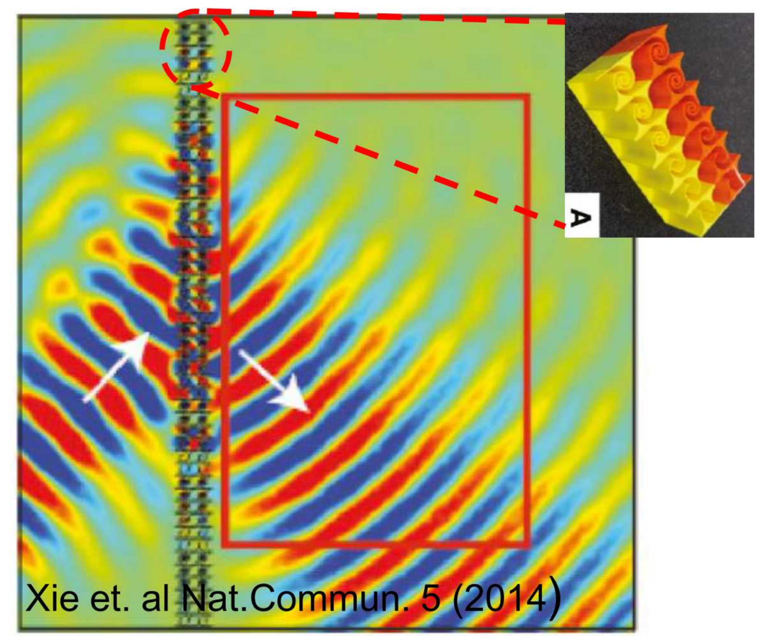
Metasurfaces vs Metamaterials

Metamaterials offer a viable approach to wave control (bandgaps, negative refraction, etc.), but their performance are limited by the wavelength.

Metamaterial



Metasurfaces



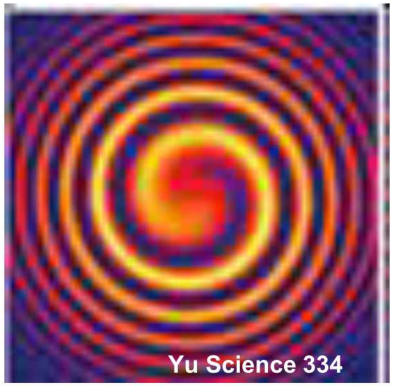
Background and motivations:

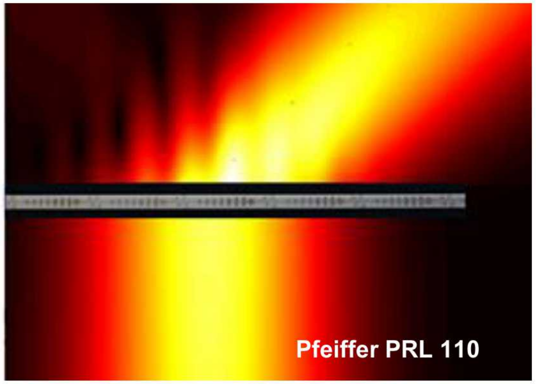
Wavefront manipulation via metasurface

The concept of **metasurface** recently emerged as an effective approach to manipulate wave-like fields while breaking the dependence on the propagation length in both optical and acoustic media.

Novel applications including:

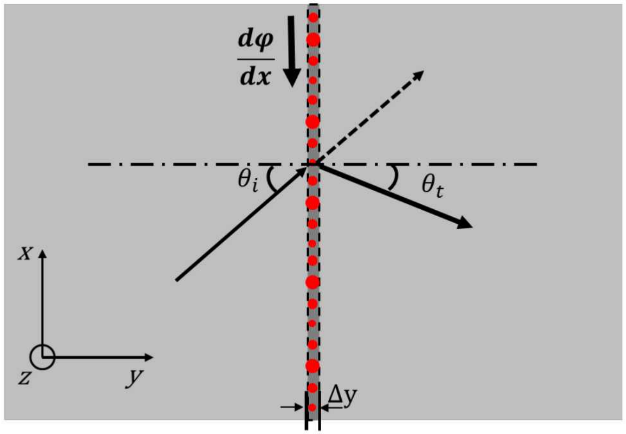
- ✓ Bending light in arbitrary shapes
- ✓ Conversion of propagating into surface modes
- ✓ Ultra-thin lenses, etc.


Yu Science 334


Pfeiffer PRL 110

The operating principle of the metasurface relies on an abrupt phase discontinuity with a spatial gradient:

$$\frac{\sin(\theta_t)}{\lambda_t} - \frac{\sin(\theta_i)}{\lambda_i} = \frac{1}{2\pi}\frac{d\phi}{dx}$$

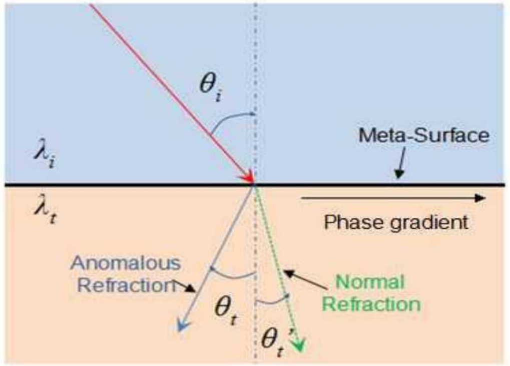


Technical approaches:

Total-internal-reflection metasurface

Generalized Snell's Law

$$\frac{\sin(\theta_t)}{\lambda_t} - \frac{\sin(\theta_i)}{\lambda_i} = \frac{1}{2\pi}\frac{d\varphi}{dx}$$

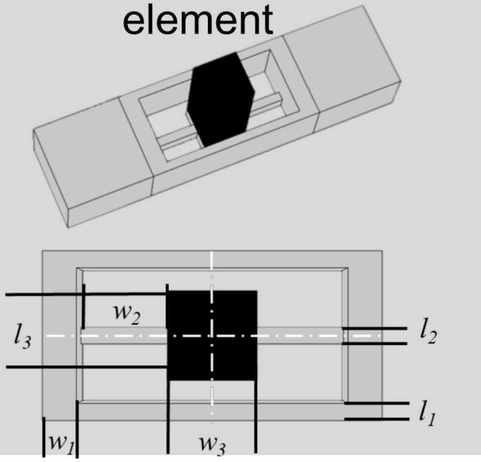


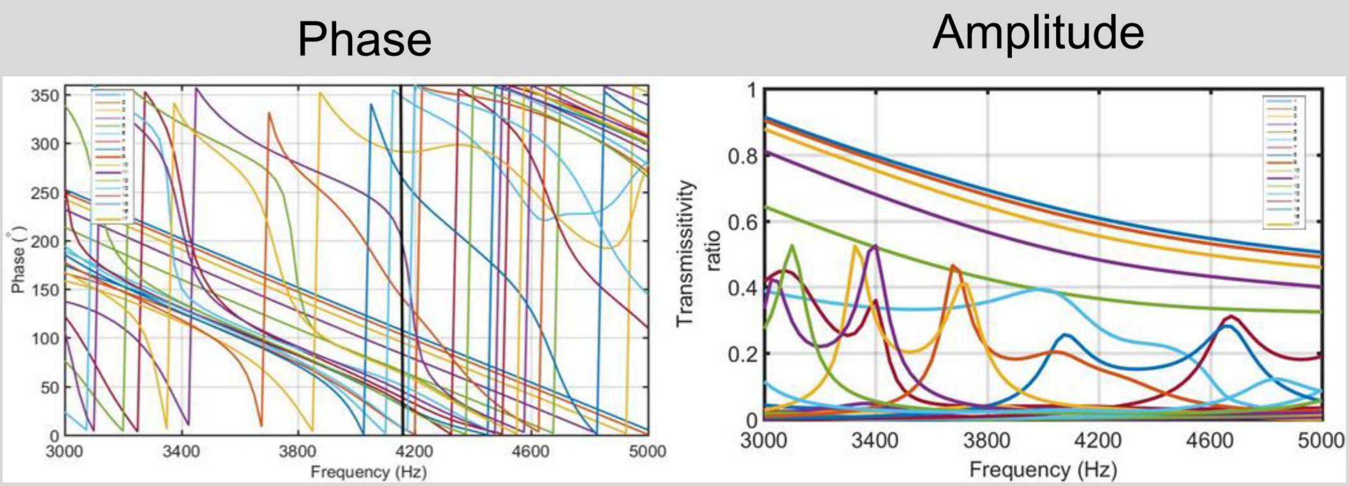
Under deep subwavelength conditions, the phase gradient could be designed so that no refracted wave exists. This condition is known as total internal reflection.

$$\boxed{\frac{\lambda}{2\pi}\frac{d\varphi}{dx} \geq 2}$$

Unit cell designs:

- ❑ locally resonant element

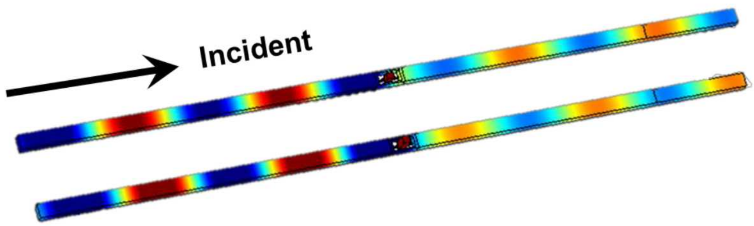


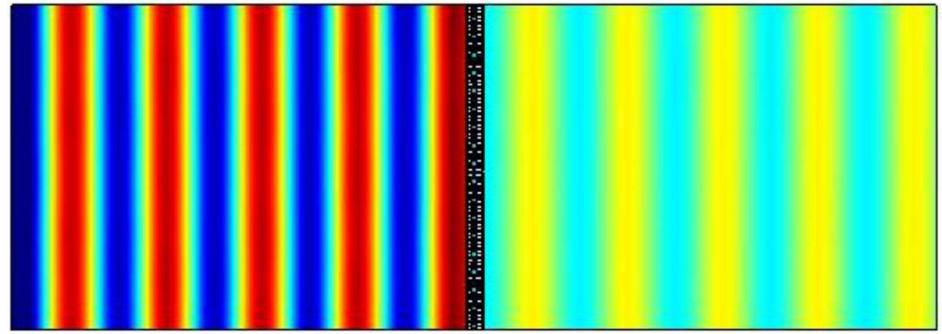


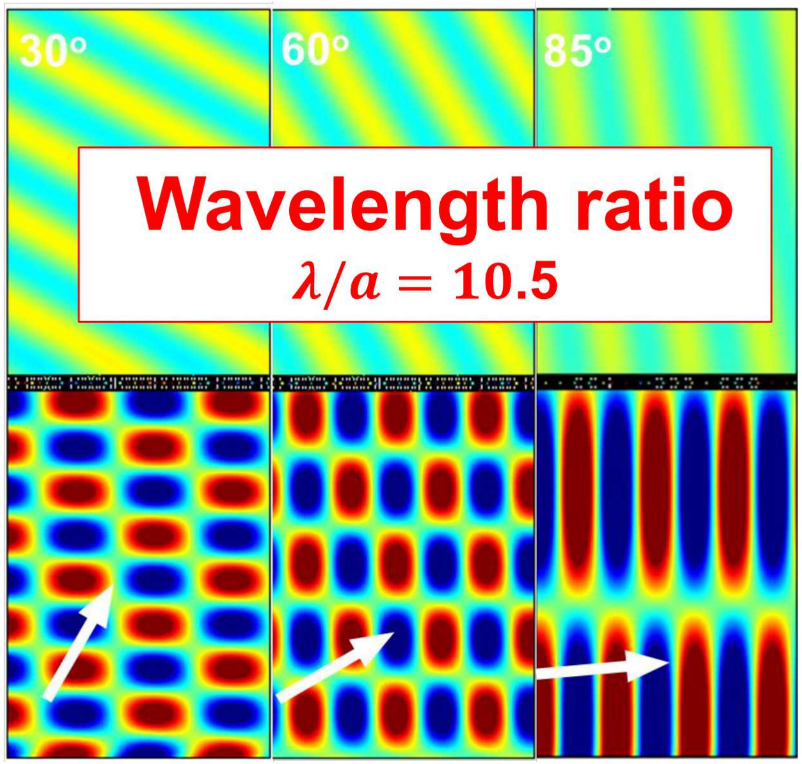
By adjusting the units' geometries, their phase and amplitude can be efficiently tuned to cover the required 2π range.

Total-internal-reflection metasurface:
A0 mode excitation

Target frequency 5500 Hz

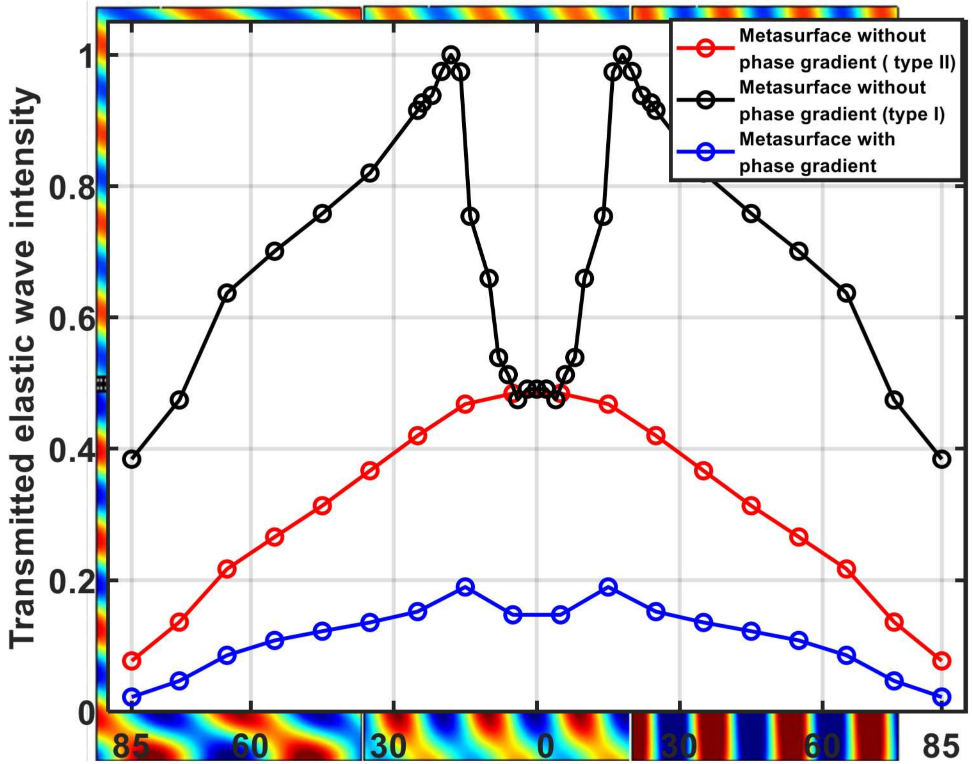






Wavelength ratio

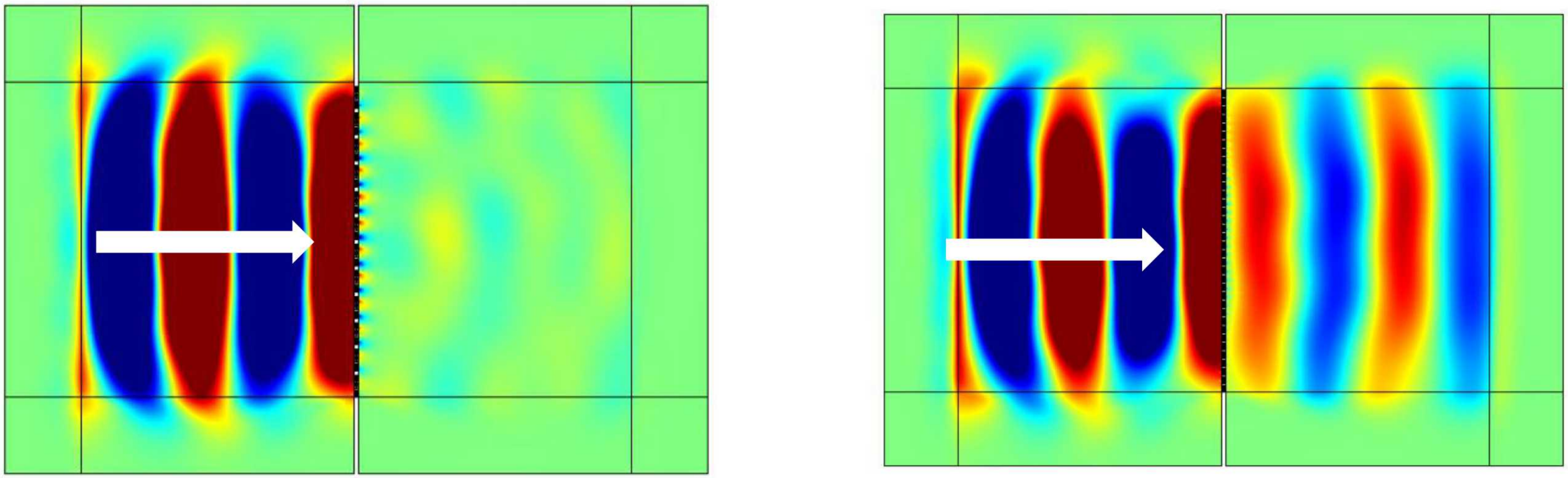
$\lambda/a = 10.5$



Total-internal-reflection metasurface:
S0 mode excitation

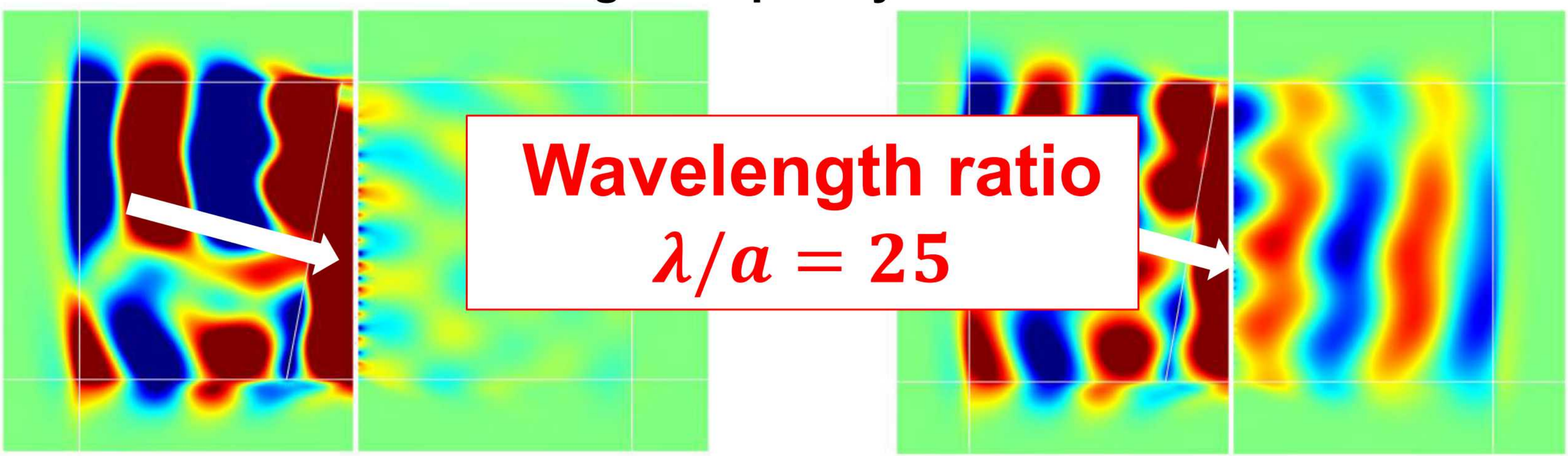
With phase gradient | Without phase gradient

Normal incidence



Target frequency 4100 Hz

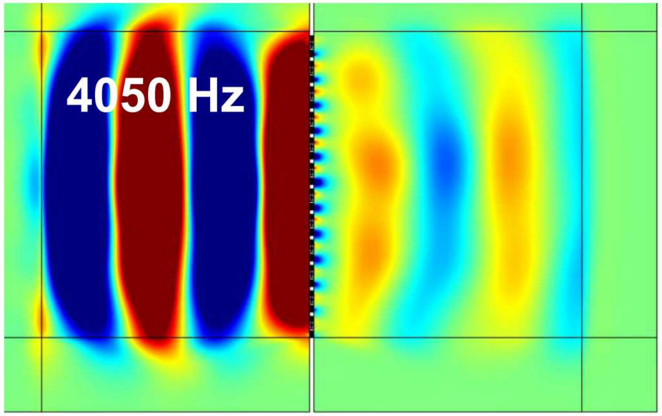
Oblique incidence

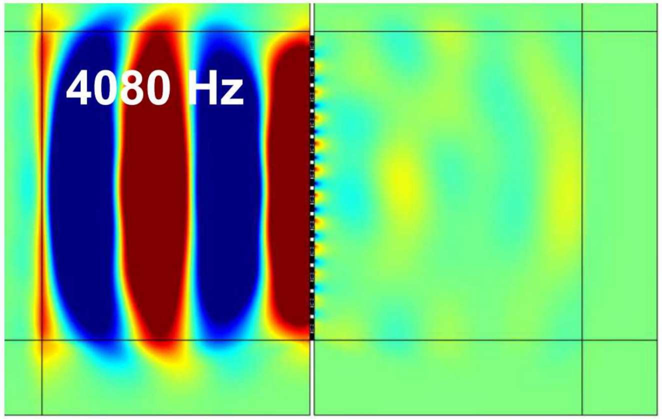


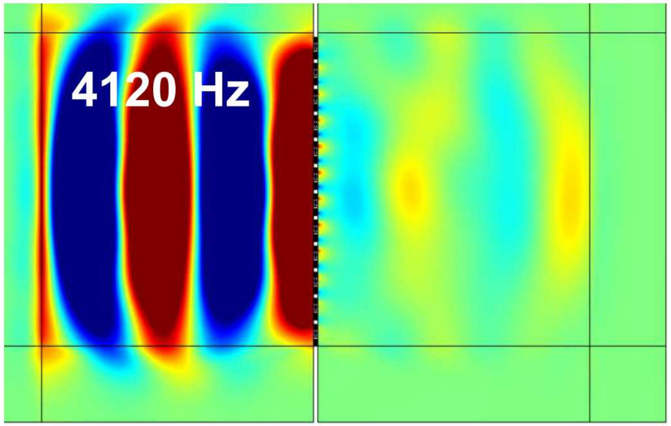
Wavelength ratio
$\lambda/a = 25$

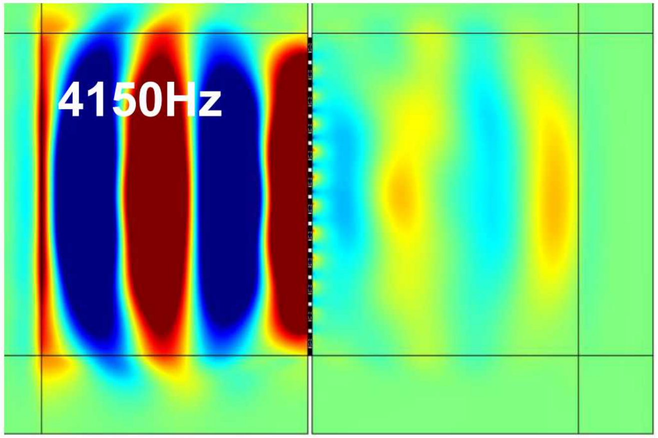
Total-internal-reflection metasurface:
Narrow band performance

When operating away from the target frequency, the performance of TIR-MS quickly deteriorates.



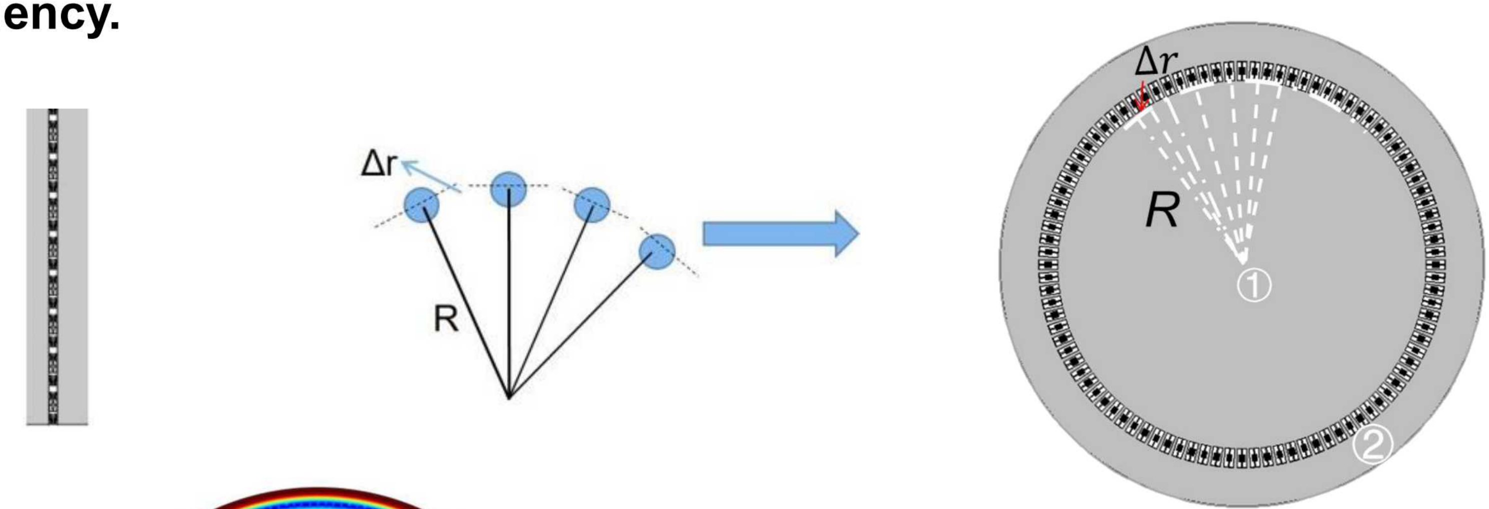




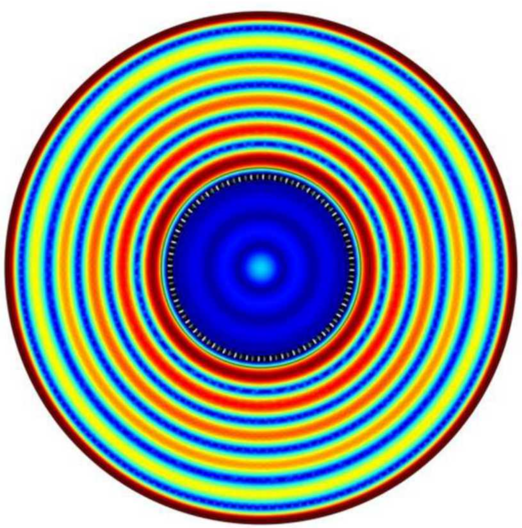


Total-internal-reflection metasurface:
Application to circular waveguide

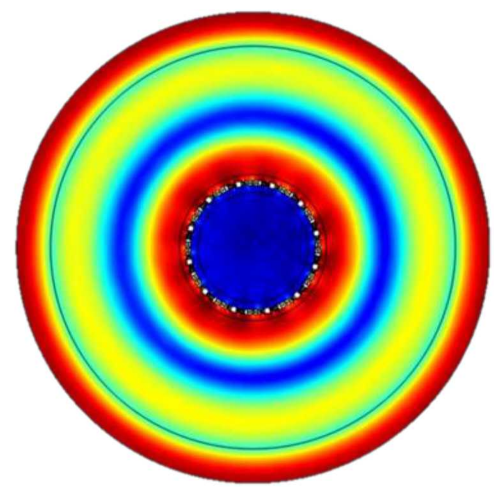
Wrap the flat MS to create a deep subwavelength sound hard barrier at the target frequency.



For A0 modes

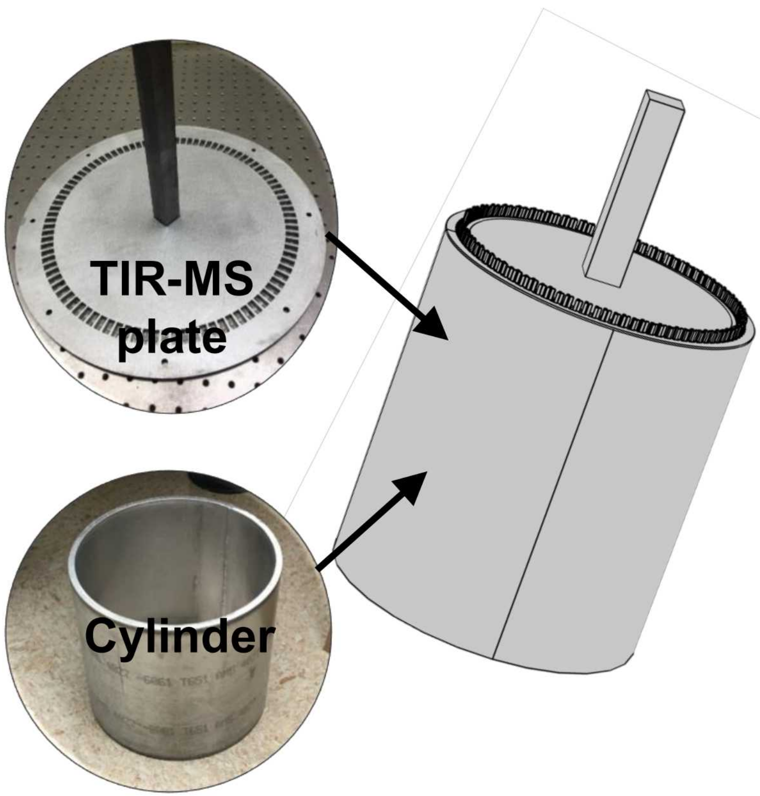


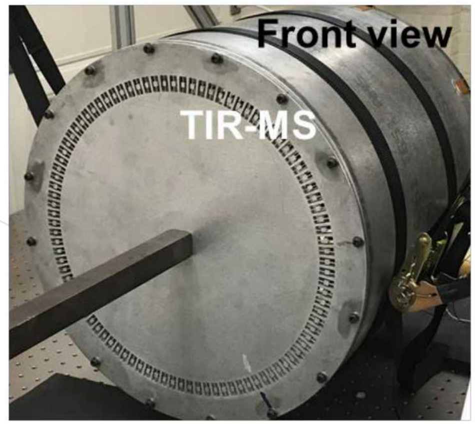
For S0 modes

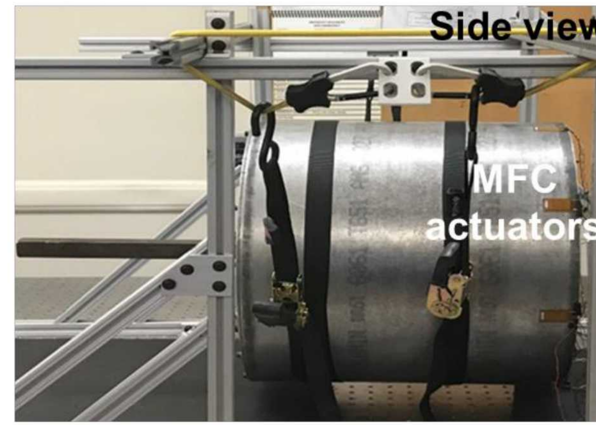


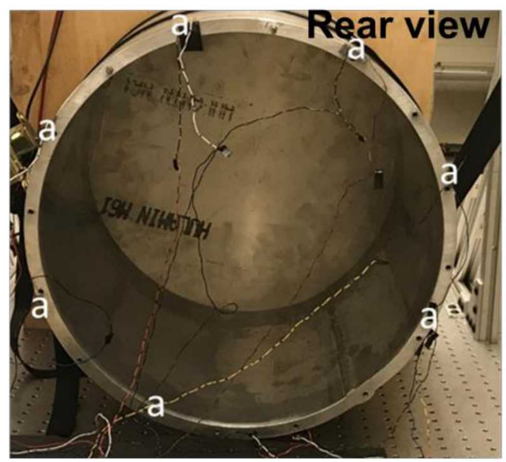
Experimental Validation:
Test on a bolted structural assembly

Mayes Cylinder Model





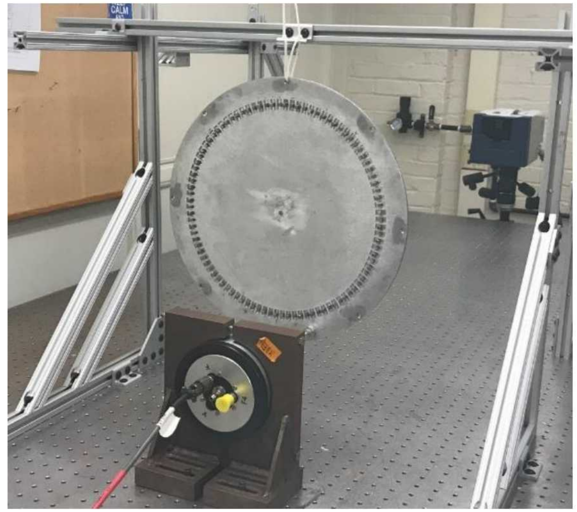


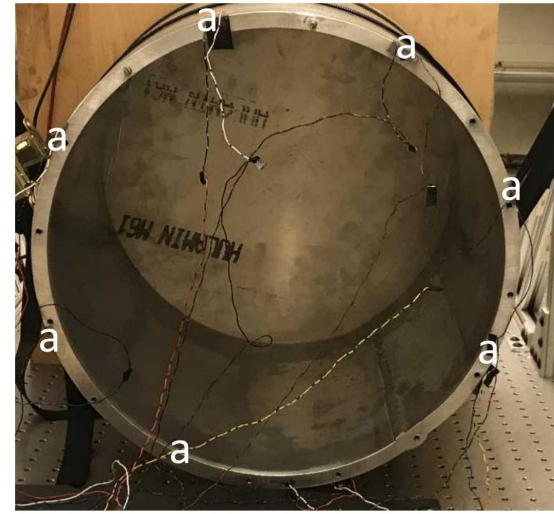


Experimental Validation :
Setup assembly and instrumentation

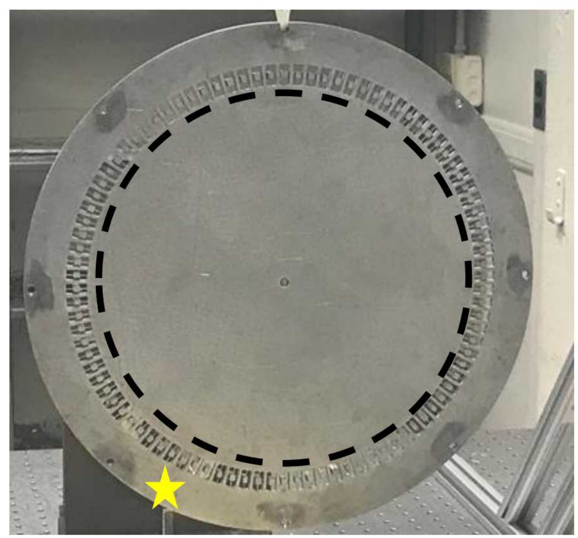
Summary of Experimental steps:

- ✓ Performed measurements on the individual plates to estimate the actual operating frequency range of the MS.
- ✓ Using MFC patches that were mounted on the cylinder's walls (see labels "a") instead of using the combination "steel plate –shaker" to deliver the excitation to the whole assembly. This approach facilitate a more uniform delivery of the incident waves to the MS plate.

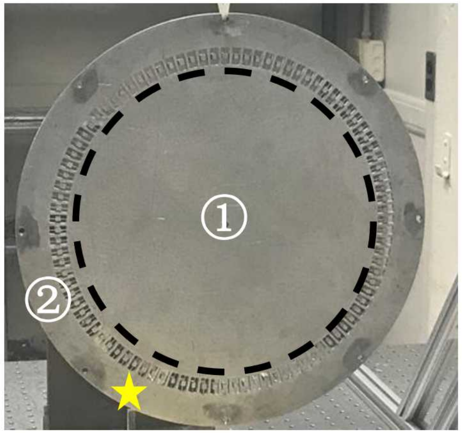




a -- MFC patch actuator



Measurements on the individual plates:
Comparison MS vs flat plate



TIR-MS @5775 Hz

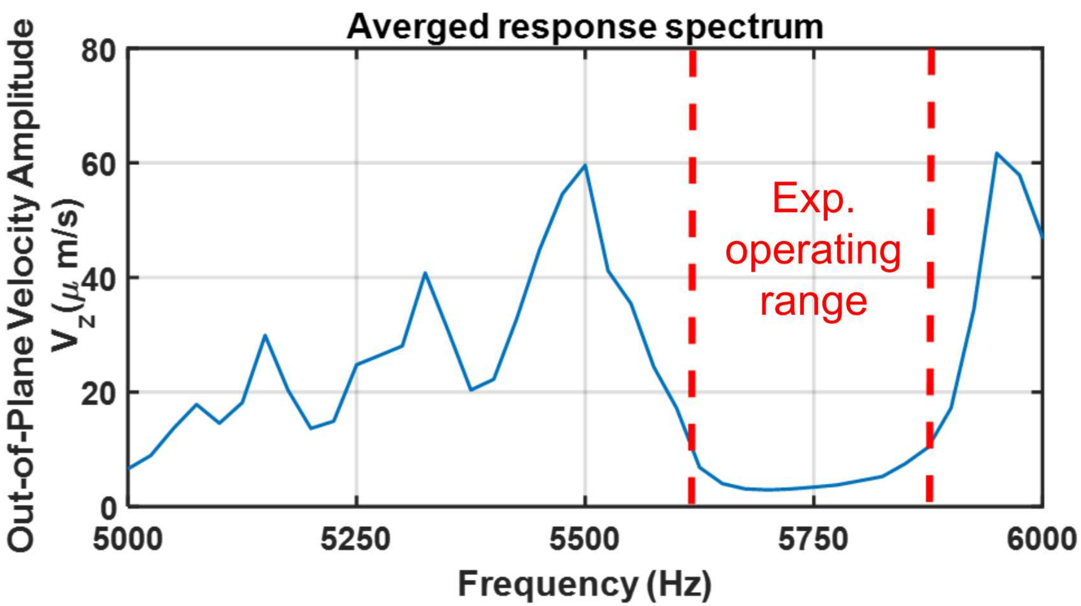
$$v_{zone1}^{MS} = 5.29\ \mu m/s,$$

$$v_{zone2}^{MS} = 52.84 \mu m/s$$

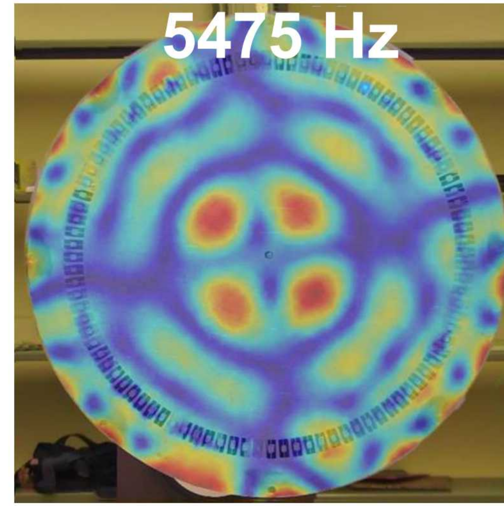
Flat @5775 Hz

$$v_{zone1}^{FLAT} = 182.11\ \mu m/s,$$

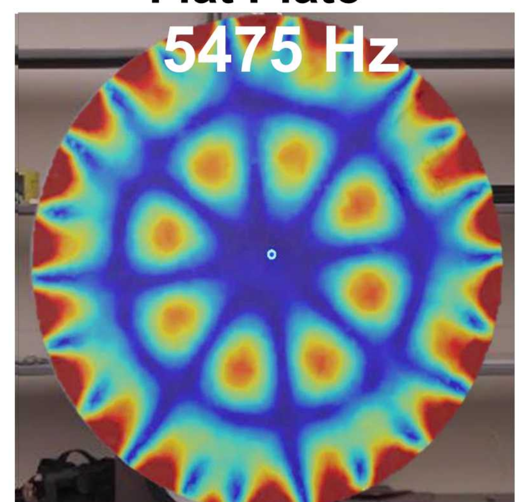
$$v_{zone2}^{FLAT} = 192.14 \mu m/s$$



TIR-MS



Flat Plate

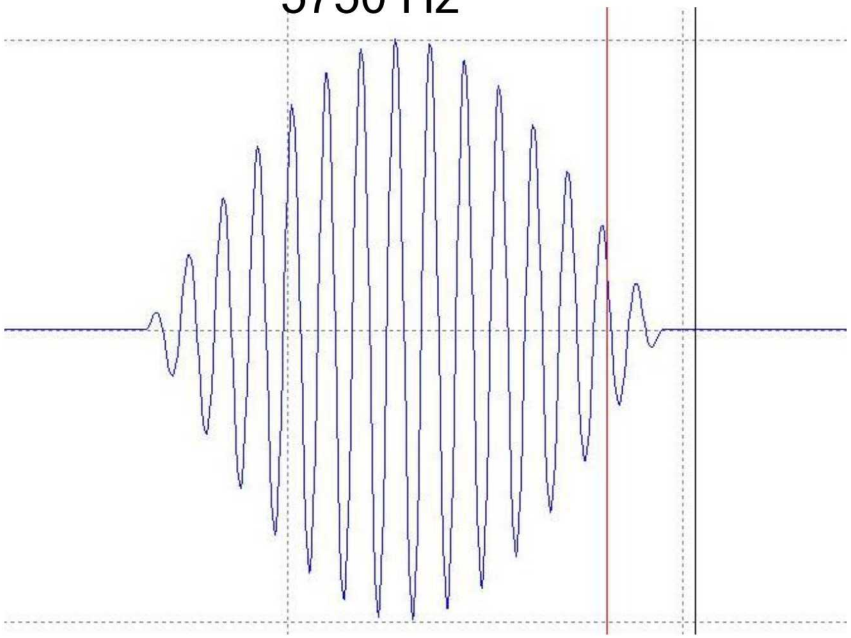


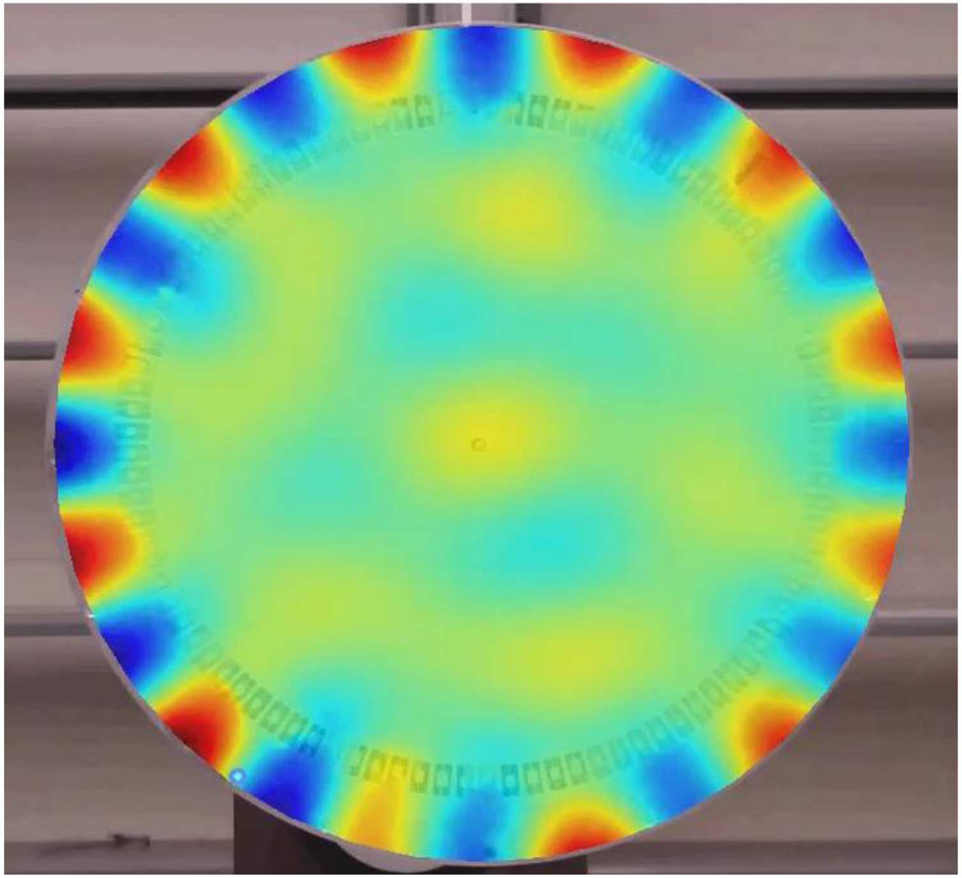
Transient measurements:

Transient response of the TIR-MS plate

Transient measurement showing the formation of the “lobed” response.

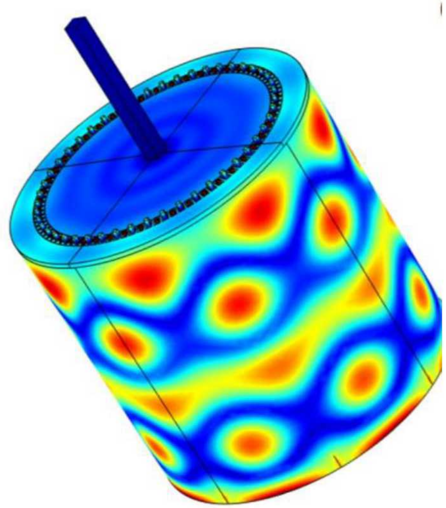
15 tones wave burst signal with central frequency at 5750 Hz

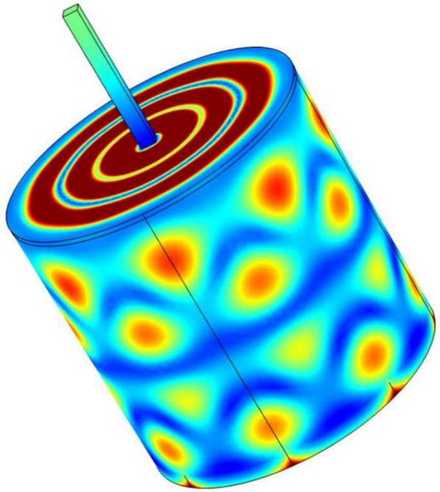


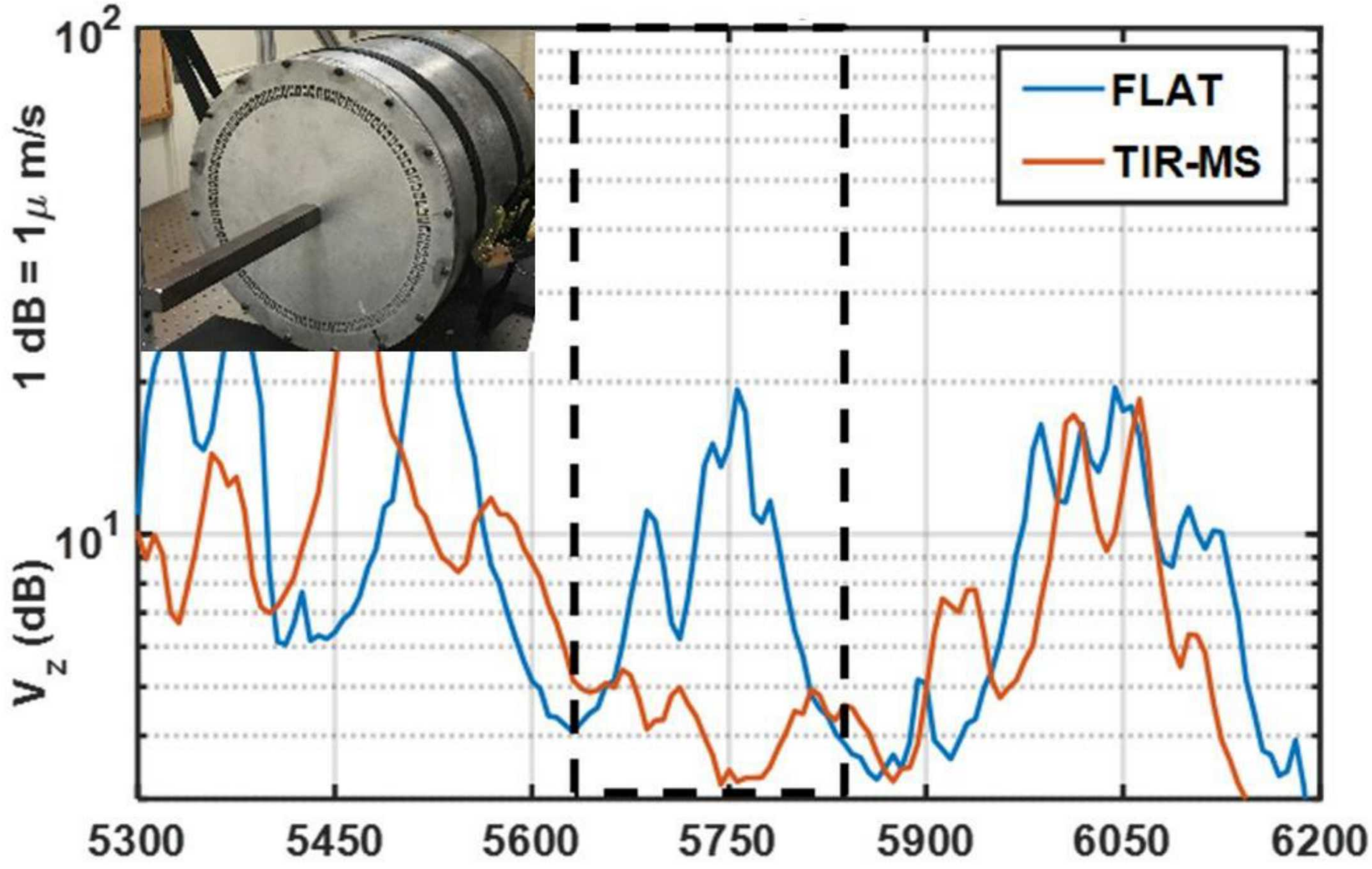


Test on the structural assembly:

Comparison between TIR-MS plate and flat plate



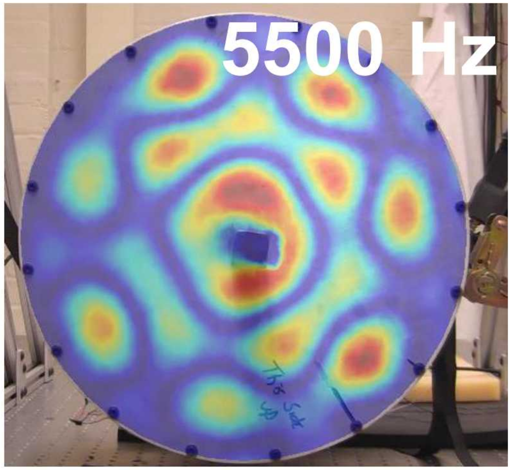




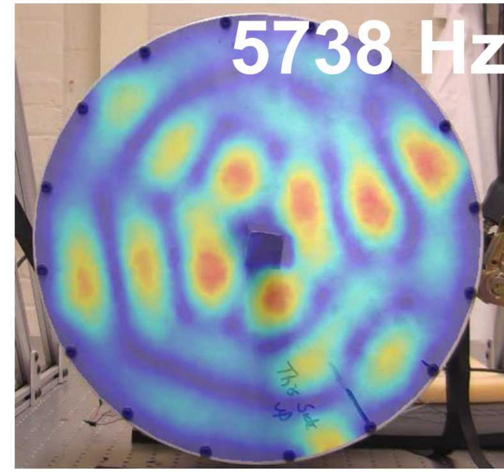
Test on the structural assembly:

Comparison between TIR-MS plate and flat plate

Outside the operating range



← Flat plate →



@5500 Hz

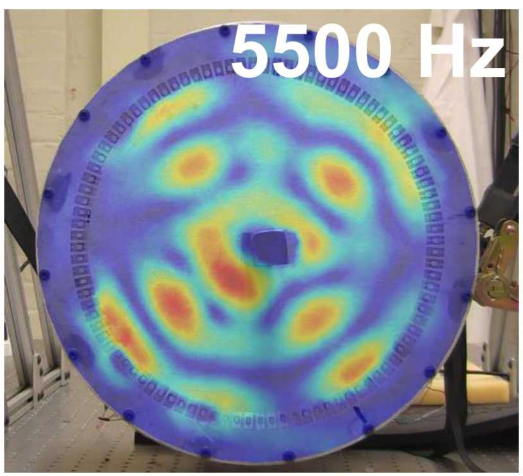
$$v_{zone1}^{MS} = 28.68\ \mu m/s,$$
$$v_{zone1}^{FLAT} = 35.35\ \mu m/s$$

@5756 Hz

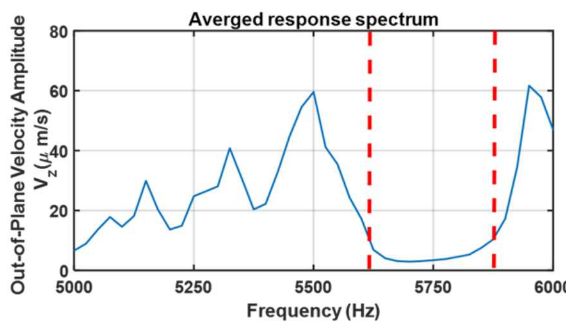
$$v_{zone1}^{MS} = 5.245\ \mu m/s,$$
$$v_{zone1}^{FLAT} = 22.36\ \mu m/s$$

$\mu m/s$: 50, 25, 0

Inside the operating range



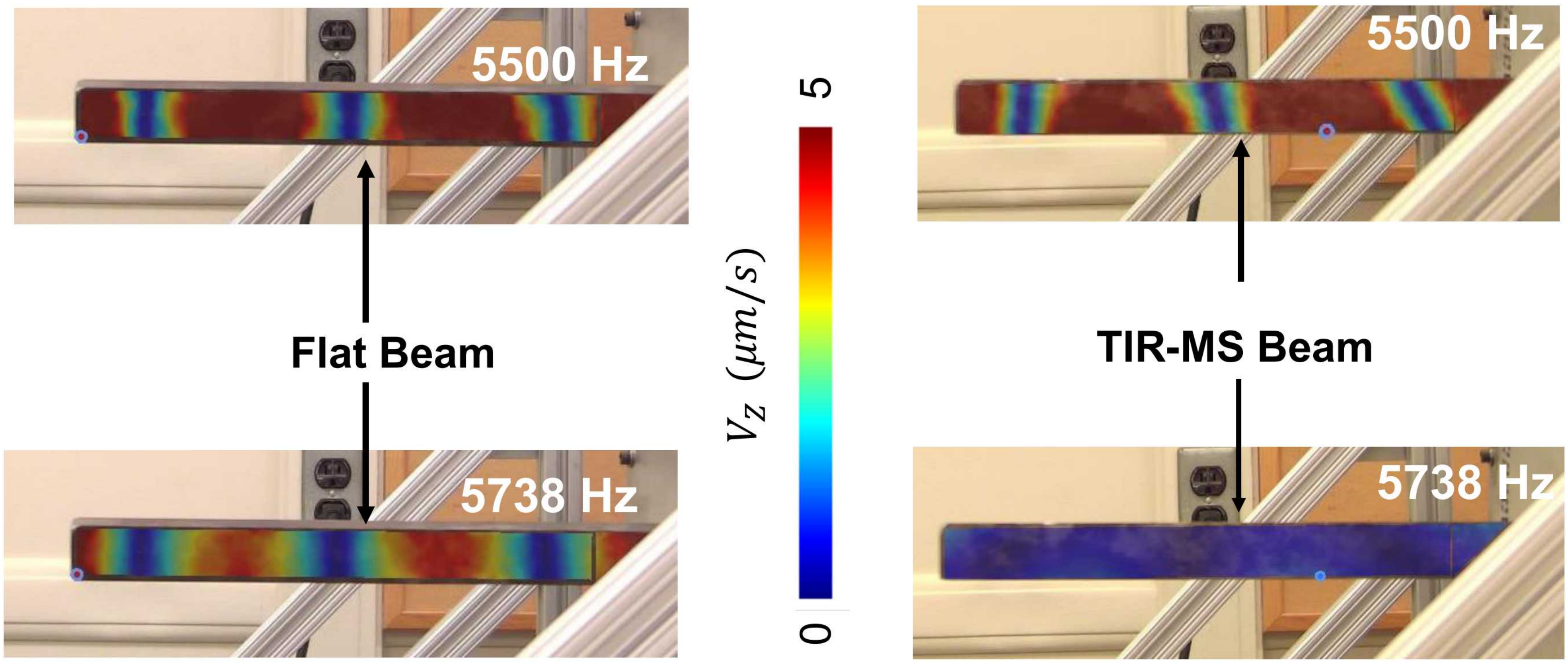
← TIR-MS plate →



Test on the structural assembly (conti’):

Scan the beam from the side

Outside the operating range



Inside the operating range

@5500 Hz $V_Z^{TIR-MS} = 3.638\ \mu m/s, V_Z^{FLAT} = 4.899\ \mu m/s$

@5738 Hz $V_Z^{TIR-MS} = 0.4684\ \mu m/s, V_Z^{FLAT} = 2.874\ \mu m/s$

Conclusions

- ✓ We have presented and experimentally demonstrated the design of a Total-internal-reflection Metasurface (TIR-MS), that can be embedded in structural waveguide so as to achieve vibration isolation effects.
- ✓ A numerical study through the finite element simulations was performed that confirms the transmitted wave energy is very low over almost all incident angles, when the proposed flat TIR-MS was applied .
- ✓ A bolted structural assembly of different waveguides involving beam, plate, and shell elements is built up for laboratory tests. The experimental works prove that the significant vibration isolation can be achieved in the presence of the TIR-MS.

Acknowledgements

The authors gratefully acknowledge the financial support from the Sandia National Laboratories under the Academic Alliance program, grant #1847039.

Sandia National Laboratories is a multi mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration. With main facilities in Albuquerque, N.M., and Livermore, C.A., Sandia has major R&D responsibilities in national security, energy and environmental technologies, and economic competitiveness.

Thank you!

Questions?