# Refracting/Reflecting ultrasonic waves by sub-wavelength elastic metasurfaces

H. Lee[1*], J. K. Lee[2], H. M. Seung[3], and Y. Y. Kim[2]

[1]Department of System Dynamics, Korea Institute of Machinery & Materials, Daejeon, Korea
[2]WCU Multiscale Design Division, School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea
[3]Center for Safety Measurement, Korea Research Institute of Standards and Science, Daejeon, Korea

[*]Corresponding author: jackwon2@kimm.re.kr

## 1. Introduction

Metasurfaces [1, 2] have recently opened doors for innovative ways to manipulate the wave fields owing to its fascinating capability of realizing the extreme features of bulky metamaterials within a much more compact and easily-fabricated form. Especially by their low-loss subwavelength scale and planar geometry, the metasurface concept completely fulfills the recent demand of maximizing the potential for practical applications. In this work, we design unique elastic metasurface structures to present both refraction and reflection functionalities for ultrasonic wave manipulations. Such capabilities are expected to provide innovative approaches regarding non-destructive evaluations and biomedical applications.

## 2. Generalized Snell's Law

The basic principle for the general metasurface is to break the classical Snell's law where the main assumption lies in the fact that phase at the boundary stays unchanged. From the Generalized Snell's law [3] that considers the extra phase accumulation within the boundary, the refracted angle of the transmitted beam can be defined as below

$$\sin \theta_t = (1/k_0)\, d\varphi/dx + \sin \theta_i \qquad (1)$$

where $\theta_i$ is incident angle, $\theta_t$, refracted angle and $k_0$, the wavenumber of outside medium. By imposing the extra phase gradient $d\varphi/dx$, we can design any artificially engineered refracted/reflected beam patterns depending on various combinations of the unit cells.

## 3. Refracting/Reflecting ultrasonic waves within the subwavelength scale

In this section, we demonstrate the refraction and reflection phenomena of ultrasonic waves within the subwavelength scale by our planar elastic metasurfaces. The designed subunits function as building blocks that are capable of inducing phase shifts ranging from 0 to $2\pi$ so that any beam patterns can be demonstrated based on limitless phase profiles.

For example, we intentionally arrayed the subunits to realize a phase profile for beam steering as shown in Fig. 1(a). The theoretical (blue solid line) and discrete (red circles) phase profile from the unit cells are shown together with the simulation. Here, the continuous phase profiles can be represented by discrete phase shifts (steps of $1/6\pi$) realized by the subunits.

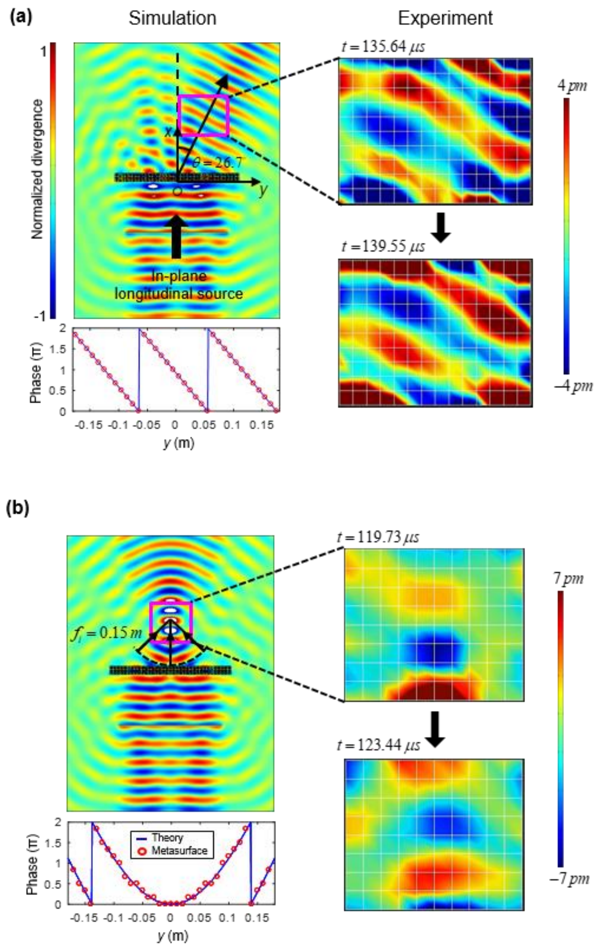


Fig.1 (a) (left) Two-dimensional simulation of refraction along with theoretical (blue) and corresponding discrete phase shifts (red). (right) Experimentally obtained displacement field. (b) (left) Flat lens simulation with the same condition. (right) Experimentally obtained displacement field on the focusing spot.

We also demonstrate wave focusing with the hyperbolic phase profile as shown in Fig. 1(b). Such functionality can be a good alternative to conventional lenses. Along with the simulations, experiments on the wave refractions are performed with a laser scanning vibrometer to measure the displacement field. As can be clearly seen from the results, both the simulation and the experiment show a good agreement.

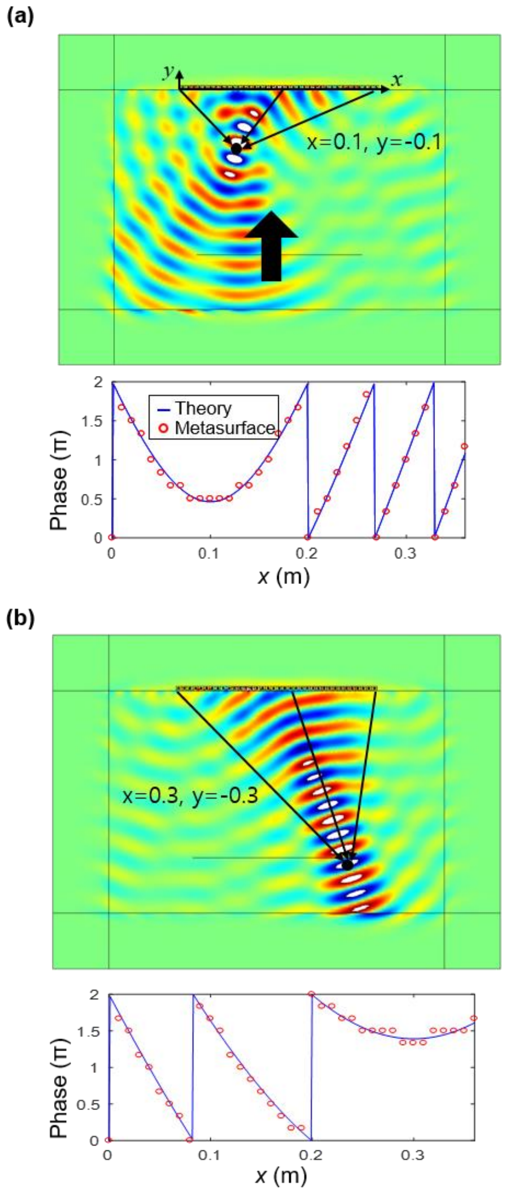


Fig.2 The simulation of reflection with phase profiles. Beams are reflected to a specific spot (a) x=0.1, y=-0.1 and (b) x=0.3, y=-0.3.

The results for the reflection phenomena are shown in Fig. 2. Here, we specially utilize a unique phase profile to focus the reflected wave into an arbitrary spot. The phase profiles show somewhat biased hyperbolic aspect. Accordingly, Fig. 2 shows how excellently our elastic metasurfaces can reflect the ultrasonic waves to the intended spots that are stated above.

## 4. Conclusion

We presented uniquely designed elastic metasurfaces to demonstrate abrupt refraction and reflection of ultrasonic waves within the subwavelength scale. The capability of beam manipulation is confirmed both by the finite element simulation and ultrasonic wave experiment. We expect this research to resolve the drawbacks of conventional ultrasonic inspection devices; the low transmission efficiency due to the bulky feature of wedge-type ultrasonic probes.

## Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) Grant [no. 2014M3A6B3063711 (Global Frontier R&D Program on Metamaterials)] funded by the Korean Ministry of Science, ICT and Future Planning (MSIP) contracted through IAMD at Seoul National University. This research was supported by the Main Project of Korea Institute of Machinery and Materials (Project Code: NK221L, NK220D).

## References

[1] X. Ni, A. V. Kildishev and V. M. Shalaev, Metasurface holograms for visible light, *Nature Communications*, 4 (2013) 2807.

[2] H. Lee, J. K. Lee, H. M. Seung and Y. Y. Kim, Mass-stiffness substructuring of an elastic metasurface for full transmission beam steering, *Journal of the Mechanics and Physics of Solids*, 112 (2018) 577-593.

[3] N. Yu and F. Capasso, Flat optics with designer metasurfaces, *Nature Materials*, 13 (2014) 139-150.