Optimizing Inverse Phononic Crystals on GaAs for Surface Acoustic Waveguiding

K. Singh[1] and J.A.H. Stotz[1]

[1]*Department of Physics, Engineering Physics & Astronomy, Queen's University,*
Kingston, Ontario K7L 3N6, Canada

jstotz@queensu.ca

This study investigates the design and optimization of inverse phononic crystals (PnCs) for enhanced surface acoustic wave (SAW) guiding on Gallium Arsenide (GaAs). Building upon the concept of an "inverse waveguide" [1], where periodic inclusions reduce the effective stiffness of the substrate, this research focuses on achieving strong SAW confinement by lowering the eigenfrequencies of the propagating modes below the bulk shear horizontal (SH) wave threshold. This confinement is crucial for minimizing energy leakage into the bulk substrate and enabling efficient waveguiding.

Previous research utilizing cylindrical inclusions demonstrated the potential of inverse waveguides but faced limitations in achieving sufficient confinement due to coupling to bulk SH modes through the inclusions [1, 2]. To address this, we systematically explore various inclusion shapes using finite element method simulations in COMSOL Multiphysics.

Figure 1 shows the band structure obtained through eigenfrequency analysis for an elliptic cylinder inclusion with dimensions of $3\mu m \times 1\mu m \times 3\mu m$ (length × width × depth) embedded in a GaAs substrate with a lattice parameter of $4\mu m$. The direction of wave propagation is along the short axis of the inclusion. To ensure accuracy, rigorous mesh and boundary sensitivity studies were conducted. The data is then filtered to select modes polarized in the *xz*-plane and confined near the surface. Logarithmic reciprocal attenuation, defined by $-\log_{10}[\mathrm{Im}(\omega)/\mathrm{Re}(\omega)]$, is used as a figure of merit for defining confinement to the surface.

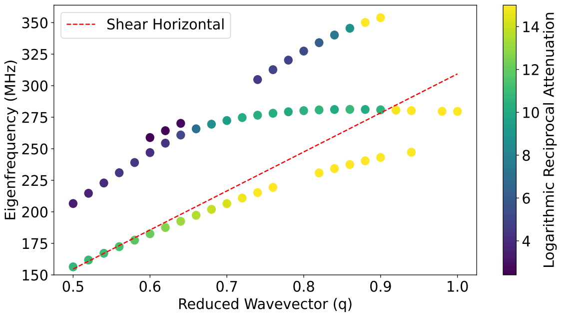

Fig. 1. Band diagram showing surface modes for elliptic cylinder inclusion $3\mu m$ long, $1\mu m$ wide and $3\mu m$ deep. Higher logarithmic reciprocal attenuation values correspond to stronger confinement and less energy leakage into the bulk.

As can be seen in Figure 1, modes larger than reduced wavevector, $q = 0.62$ exhibit eigenfrequencies below the SH threshold, limiting coupling into the bulk and slowing the wave sufficiently for effective waveguiding.

Figure 2 shows the total displacement magnitude for the lowest order mode of a four-inclusion waveguide operating at $q = 0.74$. This waveguide structure was designed by placing four elliptic cylinder inclusions side-by-side, forming the width of the waveguide. As can be seen in the figure, this design achieves strong confinement in all three directions.

This waveguide design also demonstrates a tenfold improvement in logarithmic reciprocal attenuation compared to previous designs utilizing cylindrical inclusions [1]. These characteristics make it a promising candidate for efficient on-chip SAW waveguiding, with potential applications in building complex acoustic circuits for a variety of applications, including quantum spin transport, where the piezoelectric properties of GaAs can be leveraged for manipulating electron spins. [3]

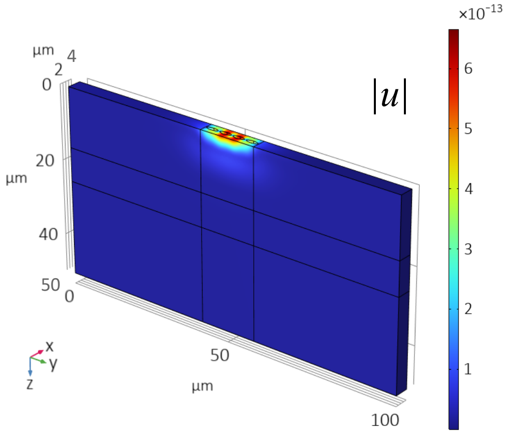

Fig. 2. Total displacement magnitude for the lowest order mode of a four-inclusion ($16\mu m$) wide waveguide at $q = 0.74$

References

[1] E. Muzar and J. A. H. Stotz, Crystals **13**, 1540 (2023).

[2] E. Muzar and J. A. H. Stotz, J. Appl. Phys. **126**, 025104 (2019).

[3] P. L. J. Helgers, J. A. H. Stotz, H. Sanada, Y. Kunihashi, K. Biermann, and P. V. Santos, Nature Communications **13**, 5384 (2022).