Phononic crystal strips for engineering micromechanical resonators

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Periodic microstructures with ultrasonic stop bands improve microresonator performance that approaches material limits by thoroughly eliminating radiated energy loss.

Micromechanical resonators are circuits tuned to particular frequencies that have broad application in electronic and communication systems. Silicon-based resonators also have the advantage of economy by virtue of their compatibility with integrated-circuit fabrication technology. A key issue for these resonators is a high quality (Q) factor (a key indicator of performance), which is essential for alleviating ‘close-in’ (phase) noise in timing devices. To achieve this performance, resonator energy loss—due either to damping or radiation—needs to be kept as low as possible. Damping loss establishes the material limits to reaching an effective Q factor, whereas radiation loss is a byproduct of the energy transmitted by acoustic wave propagation from the resonator through its support structure into a substrate.

Completely eliminating acoustic radiation loss is difficult, although numerous approaches have been described. The simplest of these involves supporting resonators at their nodal points of oscillation to the substrate. More effective methods are based on acoustic impedance mismatch, for instance, quarter-wavelength support beams for effectively reflecting outgoing waves back to the resonators. However, to thoroughly eliminate radiation loss through supports, we developed a periodic microstructure possessing an ultrasonic stop band, or phononic crystal (PnC) strip (see Figure 1). The device halts acoustic wave propagation at a particular frequency.

A PnC strip can be regarded as a 1D periodic strip structure. We explored these strips based on our experience with so-called PnC slabs, which exhibit a frequency range (or frequency bandgap) that prohibits acoustic waves of any kind from propagating. We combined PnC strips and acoustic resonance cavities. Figure 1(b) shows our architecture, and Figure 1(a) a conventional design. The resonator consists of a bar-type resonance cavity anchored to the substrate by two PnC strips at its two ends. When the bar is actuated by electrostatic force at its natural frequency, it accumulates acoustic energy and resonates. Effectively trapping the resonance energy in the cavity, which our PnC strips can do, enhances the Q factor of the resonator.

Figure 2 shows the theoretically predicted power transmission spectra of acoustic wave incidence with particle vibrations in different directions through the PnC strip. At frequencies of...
approximately 212MHz, the transmitted wave power decreases to extremely low levels (less than −100dB), regardless of the vibration. This shows the ability of the PnC strip to stop wave propagation. The underlying physics involves the PnC strip structure scattering the acoustic waves, analogous to photonic bandgaps, and forming an ultrasonic energy gap in the relevant frequency range.

PnC strips can potentially be used to engineer various micro-mechanical resonators for eliminating radiation loss or confining acoustic energy. Figure 1(d) shows microfabricated bar-type and ring-type resonators with PnC strips as lossless supports. We made these microstructures using a silicon-on-insulator wafer and nanogap technique.

Figure 3 displays simulated acoustic radiation loss. The acoustic wave fields of the bar-type micromechanical resonator are actuated in a width-extensional resonance mode. Figure 3(a) shows the conventional design with acoustic wave energy radiating through the simple support beam. By contrast, Figure 3(b) shows a resonator anchored by our PnC strips and operated at the resonance frequency in the bandgap. The acoustic radiation loss is nearly completely suppressed, leading to a high Q factor near the material limits. Figure 3(c) compares the case of a resonator designed to operate outside the bandgap of the PnC strip. In this case, acoustic radiation loss may occur without meeting the bandgap.

In summary, we have described novel PnC strips that exhibit an ultrasonic bandgap and, accordingly, enable effective Q resonator architecture using the strips as lossless supports. The architecture for silicon-based micromechanical resonators provides a guideline for a variety of resonators that require support structures for practical application. We will focus our future research on developing high-performance oscillators based on high-Q resonators with PnC strips for frequency-device applications such as timers and sensors.

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