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# Phononic Crystals Applied as Ultrasonic sensor for Liquid Systems

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Abstract

Ultrasonic sensors have a long tradition. One realization applies an ultrasonic resonator achieved by a liquid analyte confined in a solid structure. When working at MHz frequencies the characteristic dimension of the resonator, $d_{res}$, is in the mm- or upper µm-range. The primary measurement value is the resonance frequency, $f_{res}$, which is directly related to speed of sound in the liquid, $c_{liq}$:

$$f_{res} = \frac{c_{liq}}{2\, d_{res}} \tag{1}$$

A second measurement value is the *Q*-factor of resonance:

$$Q_{res} = \frac{f_{res}}{f_{FWHM}} \tag{2}$$

where $f_{FWHM}$ is the full frequency difference at half peak maximum. Both, $f_{res}$ and $Q_{res}$ depend on liquid properties like the concentration of one component in a liquid mixture. The measurement becomes an inverse problem. Quite often, one just calibrates the sensor with proper substances, although theory is available to calculate a functional relation. The resolution achievable directly depends on $Q_{res}$.

In reality, one cannot realize full reflection of the ultrasonic wave at the walls of the cavity. One actually needs a certain amount of coupling, when a piezoelectric transducer realizes electromechanical signal transduction. In consequence, both, $f_{res}$ and $Q_{res}$ systematically deviate from eq. 1 by some amount.

A fascinating idea to design a resonant sensor is the exploitation of phononic crystals. A phononic crystal (PnC), an engineered material characterized by a periodic array of scattering inclusions in a homogeneous host matrix, exhibits bandgaps, where propagation of acoustic waves is forbidden (significantly decreased in experiment). This property allows for an optimization of ultrasonic resonant sensors via control of acoustic wave propagation within the sensor. We shortly introduce the transduction concept behind 1D- and 2D-PnC sensors. Whereas the 1D-PnC sensor can be analytically treated e.g. via a chain matrix approach, the 2D-PnC requires advanced methods of numerical computation. The measurement chain allows a direct calculation of the electrical response, e.g. to changes in liquid properties. The other way around is not possible. For example, the effective acoustic impedance, $Z_{a\ liq}$, is a function of the characteristic acoustic impedance, $Z_{liq}$, of the material and the phase shift the ultrasonic waves undergoes while propagating through this layer:

$$Z_{a\ liq} = \mathrm{j}\, Z_{liq} \tan\left(\frac{\omega d_{res}}{Z_{liq}}\right) \tag{3}$$

Since $Z_{liq} = \rho_{liq} c_{liq}$ ($\rho$ is the density), $c_{liq}$, cannot be analytically isolated. It is a complex number, which considers acoustic energy dissipation as well. The optimal relation of resonance bandwidth and amplitude of the resonance is the key to an enhanced sensitivity of the sensor to liquid analyte properties and an example of the analysis of a 1D-PnC ultrasonic sensor.

We finally extend our view to a new 2D PnC sensor design concept: The analyte-filled point defect extends to an analyte-filled capillary in the 3rd dimension. This is the step toward the integration of a PnC with microfluidic elements.

We conclude from our analyses, that the ultrasonic PnC-sensor can reach a frequency resolution better than $10^{-6}$ the probing frequency. This results in a resolution in speed of sound of appr. 1 mm $s^{-1}$ taking water as an example or a resolution in the molar fraction of alcohol in water of about $5\,10^{-5}$.