

A Metasurface Acoustic Fabry-Perot Interferometer for Ultrasonic Passive Strain Sensing

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Summary:

We propose a passive strain sensor concept based on a Fabry-Perot interferometer. Its two partially transmitting acoustic mirrors consist of air-channel metasurfaces embedded in PDMS. Finite element simulations are used to design the sensor and its acoustic spectral response for 5 MHz ultrasound interrogation. This sensor exhibits an average reflectance $2.9\times$ (9.3 dB) higher compared to a PDMS monolayer, and a gauge factor of 0.48. Further simulations of lateral channel misalignment and non-circular channel cross-sections confirm the robustness of the design to fabrication variations.

Keywords: acoustic metasurfaces, passive implantable sensors, Fabry-Perot interferometer

Background, Motivation and Objective

Acoustic metamaterials have recently been explored as passive implantable sensors. Resonances or bandgap effects encode changes in pressure [1], temperature [2], or deformation [3] into a measurable acoustic spectral response. In this work, we propose an acoustic metamaterial sensor based on a Fabry-Perot interferometer, referred to as m-AFP. The device is made of two metasurfaces implemented as patterned air-channels in Polydimethylsiloxane (PDMS; Fig. 1). These act as the partially transmitting acoustic mirrors of the FP interferometer.

Here, we investigate numerically the acoustic strain sensitivity of m-AFPs as well as their robustness to fabrication variations.

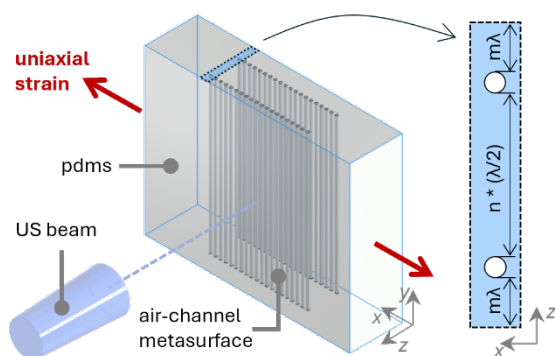


Fig. 1: Device concept. An m-AFP interferometer with air-channel metasurface mirrors. The device is strained along the x-direction and interrogated by an ultrasound probe (US beam) in the z-direction.

Description of the New Method or System

The channels are oriented along the y-direction and have a length of 3 mm, a diameter of $50\text{ }\mu\text{m}$, and a lateral lattice constant a of $100\text{ }\mu\text{m}$. The two metasurfaces are separated by $n\lambda/2$, while the PDMS cover layers extend over $m\lambda$ on both sides, λ being the sound wavelength inside PDMS at the design frequency of 5 MHz.

The acoustic spectral response of the undeformed structure was simulated in a 2D unit-cell using the pressure acoustics module of COMSOL Multiphysics. The model consists of two air inclusions in PDMS with water domains, and a perfectly matched layer above and below (Fig. 2, left). PDMS material parameters were $E = 4.5\text{ MPa}$, $\nu = 0.495$, $\rho = 1030\text{ kg/m}^3$, $c = 1030\text{ m/s}$. Water parameters were taken from the material library, and air was treated as a non-computational domain.

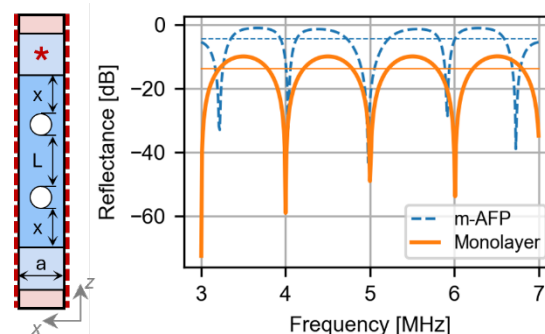


Fig. 2: Acoustic spectral response. Schematic of the m-AFP 2D unit-cell (left) and simulated reflectance spectra and average reflectance of the m-AFP compared to a PDMS monolayer of thickness L in the undeformed state (right), with $x = 206\text{ }\mu\text{m}$, $L = 515\text{ }\mu\text{m}$.

Periodic boundary conditions were applied in the x-direction. The reflectance spectrum was calculated at the point marked with ★ in Fig. 2, by subtracting dB values of the background pressure from the backscattered pressure.

Compared to a PDMS monolayer with a thickness equal to the metasurface spacing L , the m-AFP shows the same main resonances at 4, 5, and 6 MHz. However, the m-AFP exhibits a substantially higher average reflectance: -4.3 dB (m-AFP) vs. -13.6 dB (monolayer) (Fig. 2, horizontal lines). This increased average reflectance (2.9×) is a major advantage of the m-AFP, making the sensor easier to localize and increasing the signal-to-noise ratio in real world conditions.

Results

To evaluate strain sensitivity, a 3D solid-mechanics unit-cell model of the device was first simulated. Strain was applied in the x-direction, and the resulting deformation was mapped from the mid-plane of the 3D model onto a 2D geometry for acoustic simulation.

As shown in Fig. 3, tensile strain shifts the reflectance spectrum toward higher frequencies. From $f_0 = 4.98$ MHz in the undeformed state to 5.1 and 5.22 MHz for 5% and 10% strain, respectively. This corresponds to an absolute sensitivity of approximately 24 kHz/% strain, or a gauge factor $GF = (\Delta f/f_0)/\varepsilon$ of around 0.48 (similar to the monolayer), with an approximately linear scaling with strain in this range.

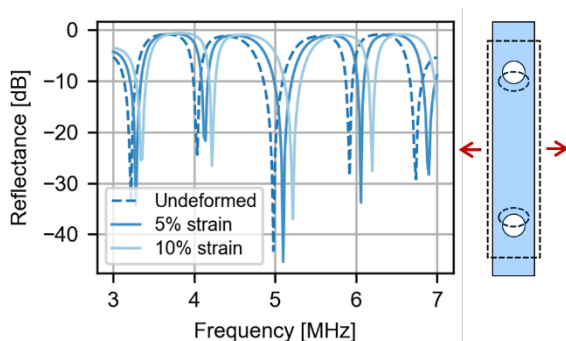


Fig. 3: **Strain sensitivity of m-AFP.** Simulated reflectance spectra of the undeformed structure as well as in the presence of 5% and 10% strain.

The robustness of the acoustic response to fabrication variations was investigated by varying the relative alignment and the cross-sectional shape of the air channels (Fig. 4). Lateral misalignment between the two metasurfaces had no visible influence on the simulated spectrum for offsets of 25 and 50 μm . Furthermore, changing the channel cross-section from circular to octagonal resulted in a nearly identical response. Square channels showed only minor deviations above 6.5 MHz, while the main resonances at 4, 5, and 6 MHz were preserved.

These results indicate that the proposed m-AFP is robust to relevant geometric variations. This is beneficial for future fabrication, as it allows different manufacturing approaches, e.g., molding from microSLA- or two-photon-polymerized masters, or soft lithography using SU-8 molds and subsequent PDMS bonding.

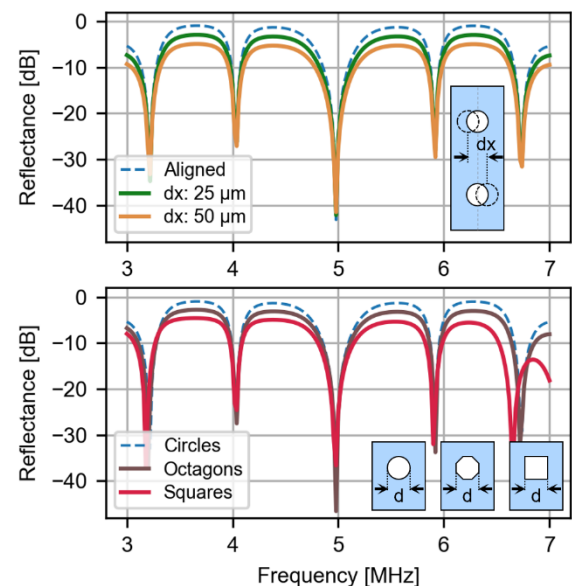


Fig. 4: **Robustness to fabrication variations.** Influence of lateral channel misalignment (top) and channel shape (bottom) on the reflectance spectrum. Curves shifted by -3 and -6 dB for better visualization.

Conclusion

We proposed a metasurface Fabry-Perot interferometer strain sensor concept. Device simulations show a high reflectance and a strain-dependent frequency shift, with an estimated gauge factor of 0.48 around the 5 MHz resonance. The response remains robust against lateral channel misalignment and moderate changes in channel shape. The proposed design combines a relatively simple two-layer geometry with passive ultrasonic readout for soft implantable strain sensors. Future work will focus on fabrication and experimental validation of the simulated response.

References

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